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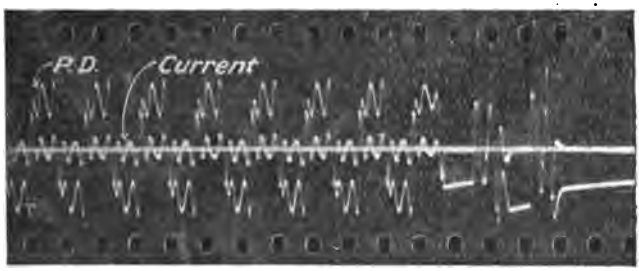

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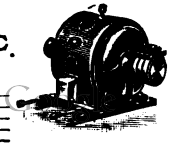

Modern Polyphase Machinery

BY

ANDREW STEWART, A.M.I.E.E.,

AUTHOR OF

"The Application of Electric Motors to Machine Driving," &c.

LONDON:
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PREFACE.

The following pages, originally a serial in *Electricity*, subsequently revised and brought up-to-date, were written with a view to giving a fairly comprehensive survey of the principles, design, and construction of modern polyphase machinery without the introduction of mathematical methods of investigation and explanation. The magnitude of such a task will be apparent, for the extensive use of mathematics has hitherto been considered absolutely essential to a correct understanding of alternate current phenomena. While this is undoubtedly true, there is no reason why it should be considered the happy hunting-ground of the mathematician; moreover, there are many engineers to whom a fairly wide acquaintance with the chief characteristics of such machinery is essential, but who have neither the time nor the inclination to approach the subject from a mathematical standpoint.

It is for such engineers that this work has been undertaken, and while it will also serve as an introduction to the subject for such students as wish a general survey of polyphase machinery before undertaking specialised work, the more exhaustive treatment of the subject, which is necessary for those who wish to become satisfactory designers, must be sought elsewhere, and for that reason numerous references have been given to other works bearing on the subjects dealt with.

The author takes this opportunity of thanking his numerous friends in Europe and the United States of America for drawings and particulars, while to the British and foreign manufacturers who supplied drawings of their machinery and apparatus he begs to express his appreciation of their courtesy.

ANDREW STEWART.

LONDON, *May*, 1906.

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MODERN POLYPHASE MACHINERY.

By ANDREW STEWART, A.M.I.E.E.

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CHAPTER I.

INTRODUCTION.

Although the first practical machines for electric lighting were alternators producing single phase alternating currents for lighting with the Jablochkoff candle, there was a period, a few years ago, when, in this country at any rate, it appeared as if direct current would swamp alternating systems; the conversion of several stations from single phase alternating to direct current, tending to make this feeling still more pronounced. With the growth of the demand for electric supply came a gradual recognition of the limitations of direct current, as it became necessary to erect large stations outside the area of supply having generating units of large capacity, and supplying alternating current which, at various points within the area of supply, was converted to direct current, though even this conversion has been abandoned in many cases for polyphase throughout, as at Dublin, Erith, &c., with three-phase distribution, and Sheffield, Coventry, Leeds, and other places with two-phase. These systems have been forced upon many large cities by the fact that, even with 500-volt feeders and 250 volts at consumer's terminals,

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the capital outlay and losses in low pressure direct current systems rendered them unsuitable to meet the enormous and rapidly increasing demands for electricity, not only for lighting, but for power, which latter purpose seems to become more important day by day.

The growth of the application of polyphase currents for purposes other than transmission only was less rapid in Great Britain than abroad. There were two reasons for this; one was that, owing to the close proximity of our principal industrial centres to cheap coal supply, the transmission of electricity over long distances was unnecessary, while few undertakings were sufficiently large to make the limitations of direct current severely felt. The other reason was that in this country the Tesla patents on polyphase machinery were respected, and as a result the royalties exacted by the owners of the patents were a serious barrier to the extended use of such apparatus. On the Continent few important countries respected these master patents, with the result that progress was unhampered. How much the interests of the large manufacturing firms of the Continent influenced the decision of the law courts is uncertain, but the result gave them every opportunity of gaining experience with the system, an experience which gave them a long lead in such work, and apparently justified that section of the British press which makes it a special business to advertise the fiction that we, as a nation, are rapidly qualifying as a museum of industrial antiquities.

CHAPTER II.

Elementary Alternator.

When any closed circuit is caused to cross a magnetic field in a direction at right angles to the lines of force which constitute that field, a difference of potential is induced therein; this potential is proportional to the magnetic field, and the number of conductors in series; further, if this conductor be moving

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in a field which is not uniform, such as crossing first a north and then a south pole with any considerable gap between, it will be obvious that the resultant difference of potential will be characteristic of the field through which it has passed, *i.e.*, when crossing the face of the north pole it will have one direction; when crossing the gap where the conductor cuts no lines the difference of potential will be zero, and when crossing the face of the south pole it will have a direction opposite to that induced in it when crossing the north pole; this is clearly shown in Fig. 1, where a bi-polar field is shown having a single loop wound on the armature.

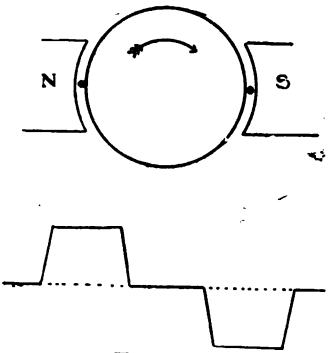

FIG. 1.

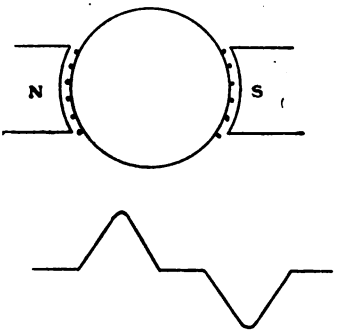

FIG. 2.

The resultant curve of electromotive force is shown below the figure, and, as will be seen, consists of a flat topped wave with steep sides and an equally flat middle portion, which corresponds to the gap between the two poles. It is obvious that this elementary alternator corresponds in no way to the modern machine, the curves of electromotive force with which every one is familiar being more rounded, and, if one may use the term, more graceful than that shown; this is due chiefly to the arrangement of the conductors in their relation to the pole pieces. Fig. 2 will show this relation, the resultant E.M.F. curve being shown below the pole pieces. Here we have six conductors which traverse

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the area embraced by the poles, and if these are looped as shown, we have an E.M.F. curve which, although peaked, more nearly resembles the curve of a modern alternator, though differing from it in that the flat portions still exist, at each change in the direction of the E.M.F. In order to completely eliminate these flat portions, either the coil or the pole faces must be widened; in fact, modifications of one or the other will result in curves which differ considerably in shape. Fig. 3 shows a machine with the poles and coils widened to give a more uniform curve of E.M.F. and one which, as will be seen, has a much larger area, and therefore, for given linear dimensions of the machine, suitable proportioning of the coils and pole

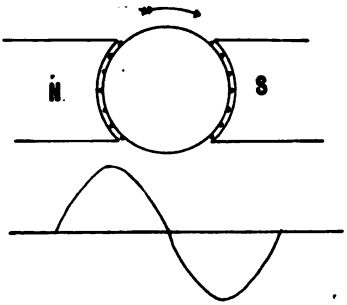

FIG. 3.

faces will enable the material to be employed in a more economical manner, so far, at least, as the production of E.M.F. goes. This will be seen from Fig. 3, where the coils embrace about half the pole pitch, while the pole faces embrace half the circumference of the armature; it is now obvious that once the E.M.F. has sunk to zero, due to the coil having passed out of the magnetic field, the other side of the winding enters this field, but obviously the direction of the E.M.F. has changed. Thus there is no portion of the armature passing across the pole face without a gradually increasing or decreasing number of conductors also passing; the influence of this

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upon the curve of induced E.M.F. is seen from the diagram of resultant E.M.F., which is practically a sine curve.

It is clear from the foregoing diagrams that the shape of the wave of E.M.F. is influenced by the distribution of the armature winding, the pole pitch, and their relative positions during a complete revolution, in the case of a bi-polar machine, and where there are a greater number of poles, the distribution of the magnetic field during the passage of an armature coil from pole to pole.

So far the production of single phase current only has been considered, and it is an easy transition from currents of one phase to those of more than one.

Taking Fig. 3, to obtain two currents whose phase displacement was one-quarter of a complete revolution from each other, it would only be necessary to take two machines, *a* and *b*, instead of the single machine shown, and connect them rigidly together, so that when machine *a* had its coils entirely embraced by the pole-pieces N.S., corresponding to the peak of the curve of E.M.F., the coils of machine *b* would at the same moment be outside the magnetic field—*i.e.*, the windings would be passing the top and bottom of the machine where no difference of potential would be induced. Were these two armatures coupled rigidly together and driven by some source of power, an alternating current would be generated in each armature, the peaks of which would follow each other at one-quarter of a complete revolution, or three armatures might be coupled together whose armature coils were displaced one-third of the angular distance through which an armature would pass in making one complete revolution, and it will be apparent that the waves of EM.F. will follow each other in the order in which the coils themselves pass before the pole pieces, in this case three-phase currents would be produced. It is not, however, necessary to arrange two or three coupled armatures in order to obtain two- or three-phase currents respectively; all that is necessary is to so displace the various sets of armature coils upon a common armature core so that each coil passes across the

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magnetic field at the proper moment. This is clear from Figs. 4 and 5, which show elementary two- and three-phase alternators, below each of which is drawn the corresponding series of waves of E.M.F. for one complete revolution. In the two-phase machine the

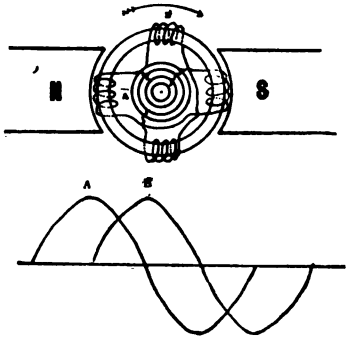

FIG. 4.—ELEMENTARY TWO-PHASE ALTERNATOR.

waves of E.M.F. have an angular displacement of 90° and in the three-phase machine 120° from each other In order to convert the machines, shown in Figs. 4 and

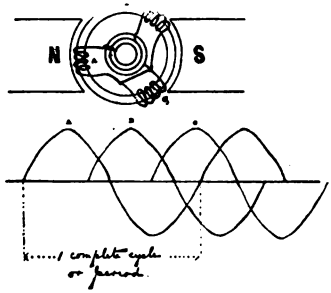

FIG. 5.—ELEMENTARY THREE-PHASE ALTERNATOR.

5, into generators of the rotating field type, now common, it is simply necessary to place the field magnet inside the armature and cause it to rotate instead of the armature.

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PERIODICITY.—It will be seen that during each revolution the wave of E.M.F. passes through a complete cycle, and that these cycles or periods are determined by the speed; for a bi-polar alternator the periods per second would be the same as the revolutions per second, or at 3,000 revolutions per minute the periodicity would be 50 per second; if there were four instead of two poles, and the speed remained the same, the periodicity would be 100, though this periodicity scarcely now exists; therefore, with four poles only half the speed would be necessary to give 50 periods. This establishes the fact that with an alternator to give a certain periodicity the number of pairs of poles will vary inversely as the speed, and thus proves the following equation :—

$$\text{Periodicity (or cycles per } \textit{second}) = \frac{P \times N}{60} \quad \text{- - - - - - - - (1)}$$

where P = the number of *pairs* of poles, N the revolutions per *minute*.

Having thus discussed the elementary alternator, we must turn to the machine as we now find it, after passing through an evolutionary process in which those machines unable to hold their own by reason of their unfitness or inability to meet modern requirements have, more or less, disappeared from electricity supply works of the present day. Before doing so we must, however, deal with the essential parts of a modern alternator—viz., the field and armature systems, the materials which form these, the insulation and its properties. It is unnecessary to treat the magnetic circuit very fully, as nearly every one is more or less acquainted with the magnetic properties of the materials used in the modern dynamo-electric machine.

The materials forming the magnetic circuit of a dynamo have an important influence upon its performance, unsuitable material results in a machine discreditable alike to the designer and the manufacturer, hence an intimate acquaintance with the chemical and physical properties of the materials employed is of the utmost importance.

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CHAPTER III.

Magnetic Properties of Iron and Steel.

If a solenoid of copper wire is taken and a current passed through it, the result will be that the solenoid will exhibit all the properties of a magnet; if a piece of iron or steel be placed within that solenoid its magnetic properties are increased many times, the exact amount depends upon the quality of the iron, and the number of turns, and the current flowing in the solenoid.

The first of these, viz., the quality of the iron or steel is one of the most important factors in alternator design. The magnetic properties of these metals depend chiefly upon their chemical composition, which is influenced largely by the process of manufacture. Cast iron, which was at one time largely employed for the field magnets of electrical machinery by reason of the ease with which it could be cast into the proper shape, has in recent years been superseded by cast steel, though in a few cases where a greater mass of metal is deemed necessary on account of structural reasons, cast iron is still employed.

The magnetic quality of cast iron is influenced largely by the amount of carbon in its composition; this is found in two states uncombined (graphitic) carbon, and combined carbon—the latter seldom reaches 1 per cent., while the former varies from 3 to 4½ per cent.; combined carbon is the most objectionable, and should not reach the figure already mentioned; it is sometimes as low as .19 per cent. Although carbon exerts a great influence upon the magnetic properties of iron, there are other influences, the presence of silicon, phosphorus, sulphur, and manganese in a lesser degree influences the results obtained, and as the iron becomes purer these latter ingredients exert a growing influence. Malleable cast iron, which is cast iron from which part of the graphite (uncombined carbon) has been eliminated, thus rendering it less brittle, is more susceptible to magnetic influences than ordinary cast iron, but this does not seem

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due to the elimination of the carbon so much as to the physical process through which it passes.

CAST STEEL, which is now largely employed, contains practically no uncombined carbon, and only a small percentage of combined carbon, $\frac{1}{4}$ of 1 per cent. or less being usual, while manganese, which in small quantities has little influence upon its magnetic properties, exists generally in a proportion between $\frac{1}{2}$ and 1 per cent., frequently less than the former figure. Although manganese in these small proportions does not influence the magnetic properties of steel, it does so very seriously when present in large quantities; for instance, 13 per cent. will make a steel casting little better than a corresponding volume of air.

Most steel makers who specialise castings for electrical purposes employ the Siemens Martin process, though the Bessemer process is equally suitable; indeed, more so, as the temperature of the molten metal can be maintained uniform till all the casts have been made, while with the open-hearth process the first and last cast frequently differ in magnetic properties, due, not to the change in the chemical composition, but to change in temperature. This is one reason why steel castings frequently exhibit unexpected magnetic results. The addition of .05 to .2 per cent. of aluminium to steel improves the casting and also the magnetic qualities of the metal at *high* flux densities. The same applies to nickel steel.

WROUGHT IRON.—Forgings of wrought iron are not now employed to any extent, if, indeed, at all, in alternator construction, chiefly because of the complex nature of the magnets; forgings do not in any way lend themselves to such structures. Fig. 6 shows magnetisation curves of iron and steel. Field magnets are generally worked at or near the upper part of the bend of the magnetisation curve, viz., at about 100,000 lines per square inch, armature cores at anything from 40 to 70 thousand lines per square inch (the latter is unusual), the teeth alone excepted, where flux densities often rise to 140,000 lines per square inch.

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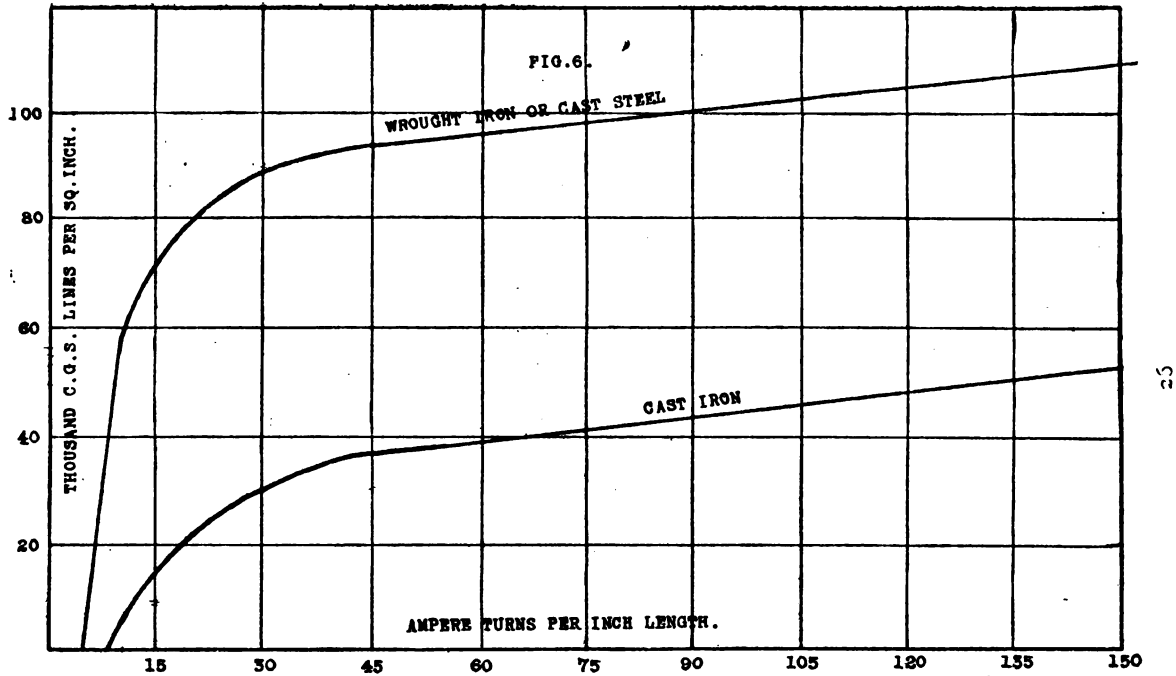

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SHEET IRON and steel, which is employed in some cases for magnet cores, frequently for pole shoes, and exclusively for armature cores, is one of the most uncertain materials used in construction, not so much by reason of the uncertainty of its composition, but the physical process through which it passes exerts a predominating influence upon its performance. Magnetically it is about equal (*) to the best steel, and the magnetisation curve for this is generally used, though frequently this is determined experimentally.

The iron in the armature passes through a cycle of magnetisation as it passes from pole to pole. These changes in the magnetisation cause losses, due to molecular magnetic friction, generally termed hysteresis, and to eddy currents. The former is proportional to the number of reversals, and increases with the magnetisation generally as the 1.5th power thereof. Mr. C. P. Steinmetz has given this as the 1.6th power. There is a difference between various experimental values, but it is small; the hysteresis loss is independent of the thickness of the iron, and its temperature; this latter is not true for temperatures above 400° F., when the hysteresis losses diminish with considerable rapidity. While the machine is in use the hysteresis loss generally increases with greater or less rapidity; it appears that the temperature at which the iron has been annealed, and its composition, exert considerable influence upon this "ageing," as it is generally called, but no very satisfactory explanation has, so far as the author is aware, been offered. This "ageing" is an important matter; indeed, machines are not unknown which now run with a temperature-rise double that originally obtained on the test plate. Several curves are given in Fig. 7 which show increases in hysteresis loss varying from 3 to 39 per cent. The working temperature has considerable influence on this ageing, above 140° F. "ageing" seems to take place more rapidly than at lower temperatures. Annealed

(*) It is about 5 per cent. better at inductions over 90,000 lines per square inch.

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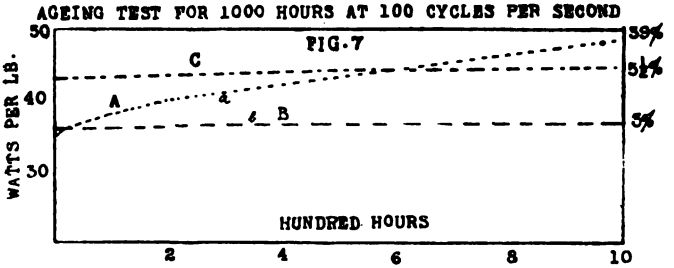
irons deteriorate more rapidly than unannealed, though irons which have low initial loss frequently age with greater rapidity. See curve (*a*) Fig. 7.

Those engaged in investigating the physical properties of iron have found remarkable changes frequently take place in iron and steel when subjected to strains. This also applies to the magnetic properties of iron. Mr. Mordey* showed some time ago that under a pressure of 1,500 lbs. per square inch the core loss in a machine increased 21 per cent. over its original value, the removal of the pressure restored this loss to its original value. This is due more to eddy currents passing between the sheets due to the decreased resistance between the sheets as these are pressed together,



than to any increase in the hysteresis loss, though the latter certainly increases. In assembling the armature cores of alternators and transformers, care must be taken that this point is not overlooked, though, on the other hand, loose core plates will cause the machine to hum badly.

EDDY CURRENTS.—Were the armature core unlaminated it would be virtually a conductor cutting the magnetic flux due to the field, and heavy currents would be induced therein, causing heating and consequent loss in power, the core is therefore laminated and the plates are japanned or varnished with some

* W. M. Mordey, "Proceedings Royal Society," January, 1895.

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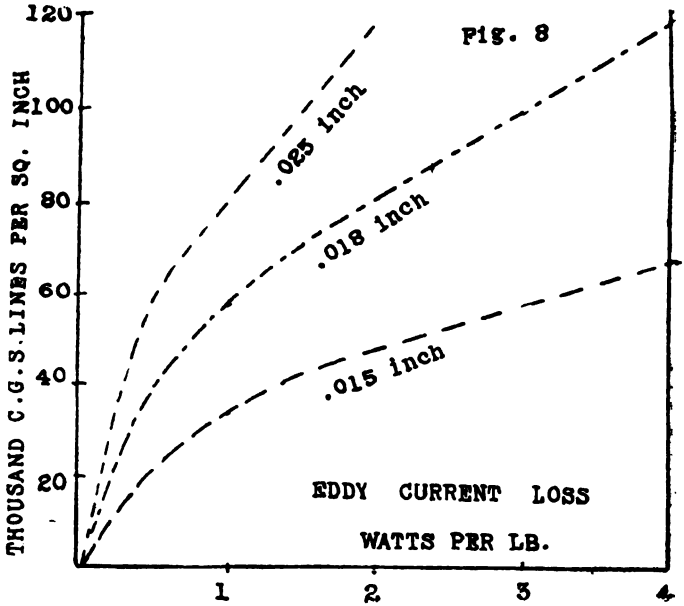
enamel which prevents, by reason of its insulating properties, the growth of large currents, often the scale which forms upon the surface of these plates is sufficient for the purpose, and not a few makers rely on this; others give the discs a coat of linseed oil—paper is not so much used as formerly; it chars, due to repeated heating, and once this has taken place it leaves the core plates loose, and the machine hums.



Even in the thinnest stamping eddy currents circulate when the machine is in operation. Iron which has a small proportion of manganese shows less hysteresis loss than when free from it, because manganese increases the specific resistance of iron. With the rise in temperature of the core the eddy currents fall off, due to the fact that the resistance of iron, in common with all other conductors, increases with rise of temperature. This eddy current loss is roughly proportional to the square

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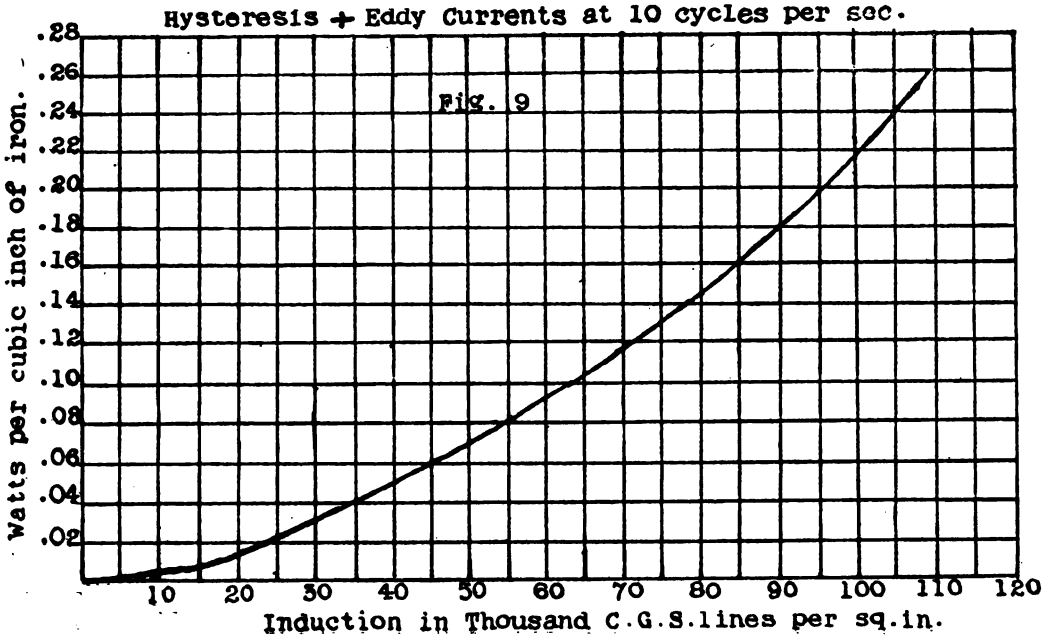

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of both the magnetic induction, and the number of reversals. Fig. 8 shows the eddy current loss per pound of iron of various thickness at varying induction, with 100 cyclic changes per second, reduced to 32° F. With higher temperatures the decrease is about .27 per cent. per degree Fah.

What is more important is the sum of these losses, *i.e.*, hysteresis and eddy currents; this is shown in the form of a curve, Fig. 9, and is for core plates .017 in. thick.

Messrs. Parshall and Hobart give in their work on Electric Generators the following formula as the general result of a number of tests on the armatures of multipolar generators. Total iron loss in Watts per pound of core = 1.7 × periodicity × flux density per square inch. It will be seen that this neglects the fact that the eddy currents increase as the square both of the periodicity and flux density, but as in practice these eddy currents form only a small proportion of the total iron loss, the above formula holds good with remarkable accuracy with the flux densities usual in modern alternators.

CHAPTER IV.

Insulators and their Properties.

The choice of the necessary insulating material for dynamo electric machinery is essentially a compromise, no material possesses all the necessary properties of high insulation, mechanical strength, ability to withstand wide and frequent changes of temperature, flexibility, and yet be proof against the absorption of even a small amount of moisture. The following table shows the voltage at which 1-1000th of an inch of the materials mentioned will break down, and the superiority of mica is at once apparent :—

Table I.

Insulating Properties of Various Materials.

Material.	Volts.	Authority.
Micanite plate ..	1,012	..Herrick and Burke.
Micanite cloth ..	439	.. „

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Table I. (continued)

Material.	Volts.	Authority.
Micanite paper ..	467	..Herrick and Burke.
Oiled muslin ..	355	.. „
Oiled asbestos	320	.. „
Single silk-covered wire	565	.. Canfield and Robinson.
Single cotton-covered wire	289	.. „
Single cotton-covered wire, coated with shellac	369	.. „
Single silk-covered wire coated with shellac	535	.. „
White Bristol board	240	.. „
Red fibre	307	.. „
Black fibre	101	.. „

Table II. shows the results obtained by various experimenters on materials having different thickness. These tests were made with alternating current, and the voltage was the effective not the maximum E.M.F. For the convenience of the reader it may be stated that when tests have been made with direct instead of alternating currents, the material, if subjected to an alternating E.M.F. will generally break down with 30 per cent. less voltage.

TABLE II.

Material.	Thickness.	Alternating E.M.F. at which it breaks down.
Mica	.004 inch	.. 14,000 volts.
Mica	.04 „	.. 45,000 „
Micanite	.039 „	.. 28,000 „
Hard rubber or ebonite ..	.039 „	.. 38,000 „
Linseed oil ..	.039 „	.. 6,000 „
Leatheroid ..	.07 „	.. 15,000 „
Oiled cotton ..	.003 „	.. 6,500 „
Oiled cambric ..	.007 „	.. 5,000 „
Oiled paper ..	.01 „	.. 5,000 „

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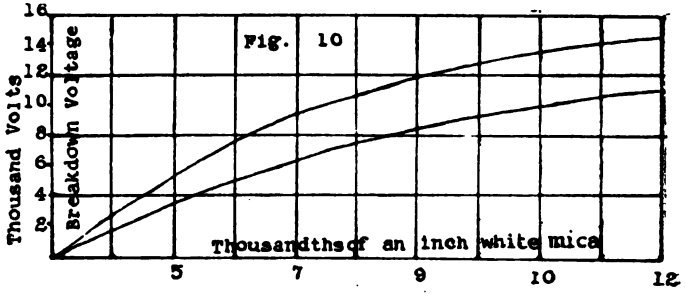
It does not follow from the above figures that the dielectric strength of insulators is proportional to the thickness; indeed, the first two instances prove that this is not at all the case; the strength *per unit* thickness is a decreasing quantity, with increased thickness, as will be seen from Fig. 10, which, although showing the results obtained for mica only, is more or less true for all other insulators. The dielectric strength of all organic materials such as muslin, linen, paper, vulcanised fibre, and similar materials, falls off with a rise of temperature. Mica and its compounds are, however, influenced but slightly; indeed, the fact that mica can stand high temperatures without deterioration and



will not absorb moisture justifies its extensive adoption. Sheets of mica, alternating with specially-prepared moisture-proof paper, micanite, and another similar compound known as megomit, are frequently employed; these compounds, by reason of their homogeneity, are rather better than mica. The two latter consist of flaked mica cemented with an insulating gum, and consolidated under great pressure, during which process it is subjected to a high temperature. This material becomes soft and pliable when its temperature is raised to 200° F., and it can then be moulded to suit curved or irregular surfaces.

One firm mills the armature slots somewhat large and lines them with thin strips of teakwood—certainly a somewhat heroic way of getting over the difficulty of

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reliable insulation, and one for which a good deal can be said.

CHAPTER V.

E.M.F. OF AN ALTERNATOR.

Having dealt with the principal components of alternating current machines, we will now proceed to deal with the considerations which determine their E.M.F.

Alternators may be divided roughly into two classes: those with alternate N and S poles, which may have rotating fields or rotating armatures, and inductor alternators, where, although the field magnet generally revolves, the exciting coil or coils are fixed; indeed, the only revolving parts are iron. The former are represented by the great majority of present-day machines, the latter by Mordey (England), Oerlikon (Switzerland), and Stanley (U.S.A.) alternators. In spite of the fact that the only moving parts of inductor alternators are iron or steel, and that a saving is effected in the amount of field copper and exciting watts, there are some disadvantages which have prevented their extensive adoption; one is that only half the armature conductors are effective (which more than offsets any saving in field copper), due to each conductor being cut by a field always in the same direction, which cuts first one side of the armature coil, and then another, not as in an alternate N and S pole machine, where the direction of the armature flux is reversed; this, however, has one advantage, that the flux density of the armature core may, for equal iron loss, be very much greater, as there is not a complete reversal of the magnetic induction, but only a change in value from maximum to minimum, and not from a maximum to a minimum in one direction, and then from a minimum to a maximum in the opposite direction. By reason of this the iron losses in the armature should be taken as only 75 per cent. of the value obtained from Fig. 9, using the same flux density.

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Generally the flux density at which inductor alternators are worked is higher than that for alternate pole machines as will be seen from Table III.

TABLE III.—USUAL FLUX DENSITIES FOR ALTERNATORS 40 TO 60 PERIODS. FIGURES ARE C.G.S. LINES PER SQUARE INCH.

	Induction Type.	Alternate pole type.
Armature core ..	78,000 to 81,000	51,000 to 53,000
Armature teeth	80,000 to 125,000	42,000 to 72,000
Air gap	70,000 to 80,000	30,000 to 42,000
Cast steel magnet cores and yokes	85,000 to 110,000	90,000 to 120,000

In order to make clear the relation between the C.G.S. system as used in many English and American text-books, and the more usual American system of naming these C.G.S. units after distinguished physicists, such as Maxwell, Weber, Gilbert, and others, the following figures are given to facilitate easy reference to standard works :—

1 C.G.S. line = 1 Maxwell.

$$\frac{\text{C.G.S. lines per square inch}}{6.45} = \text{C.G.S. lines per square centimetre.}$$

6,000 C.G.S. lines = 1 Kapp line.

930 C.G.S. lines per square centimetre = 1 Kapp line per square inch.

*H = 1 Gilbert.

H × 2 = ampere turns per inch length.

1 C.G.S. line per square centimetre = 1 Gauss.

1,000 C.G.S lines per square centimetre = 1 kilo-gauss.

On account of the fact that only one-half of the armature conductors are effective for the production of E.M.F. the number of armature turns of an inductor alternator must be double that of an alternate pole machine, making the pressure regulation poor, or alternatively the conductors may remain the same and the magnetic induction doubled; this would make the machine heavy on account of the extra iron. In practice a compromise is generally arrived at. In addition there is often

* H is the unit of magneto-motive force.

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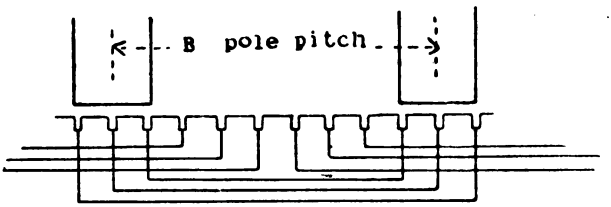
considerable magnetic leakage at the interpolar spaces; this necessitates somewhat larger field magnets, as these leakage lines are not effective for the production of useful E.M.F., indeed are often harmful by setting up E.M.F. when the curve of induced E.M.F. has reached its minimum. As will be deduced from (1) the number of poles—*i.e.*, poles of similar polarity or $\frac{\text{Total poles}}{2}$ will be

$$\frac{\text{Cycles} \times 60}{\text{Revs. per min.}} = \text{N or S poles} \quad - \quad (2)$$

The difference of potential generated in any closed circuit is directly proportional to the number of turns which constitute that circuit, the intensity of the magnetic induction interlinked with it, and the number of times this magnetic induction is changed, either, as in most inductor alternators, by increasing to a maximum and decreasing again, or, as in alternate pole generators

Fig. 11



transformers, and induction motors, first to a positive maximum, and then completely reversed, reaching a negative maximum, thus passing in the latter case through a complete cycle. We thus get for all ordinary alternate pole alternators the following formula :—

$$\text{Effective E.M.F.} = \frac{K \times M \times \text{Taw} \times n \times p}{60 \times 2 \times 10^8} \quad - \quad - \quad - \quad (3)$$

where K is a coefficient depending upon the relative values of pole width, pole pitch, and width of winding

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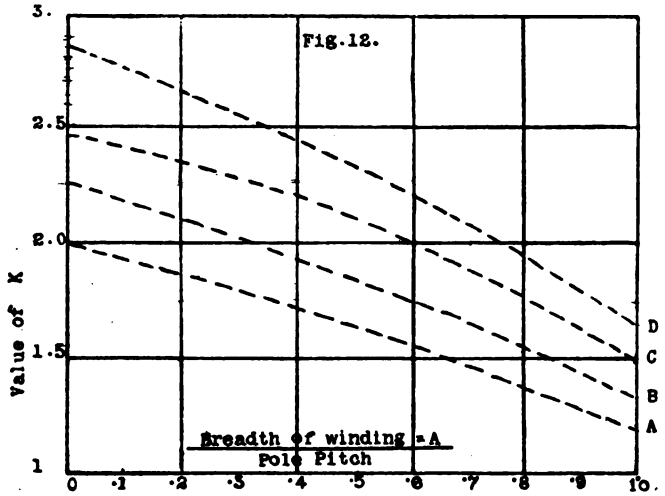
on one phase ; this is shown in Fig. 11, where the width of the winding is the distance A—*i.e.*, the distance between the outside slots carrying the winding of one phase ; the pole pitch is, of course, B. A series of curves are shown in Fig. 12 giving for A a value of $\frac{\text{Pole breadth}}{\text{pole Pitch,}}$ equal to 1 ; for B a value of $\frac{4}{5}$; for C $\frac{2}{3}$; and for D $\frac{1}{2}$, while the abscissæ represents the $\frac{\text{Breadth of winding}}{\text{Pole pitch.}}$ The ordinates give the value K, which is used as a multiplier. Curves A and B stand for inductor alternators where the ratios of $\frac{\text{Pole breadth}}{\text{Pole pitch}}$ are 1 and $\frac{4}{5}$ respectively, while C and D are for alternate N and S pole machines. In the case of inductor alterna-



tors, it must be noted that the pole pitch is only *half* the distance between two similar poles—*i.e.*, half B (Fig. 11), if B is, as in an inductor alternator, the distance between two N or two S poles. The curves, Fig. 12, are only correct for one slot per pole and phase,

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for a greater number of slots K is about 5 per cent. less. K really gives the ratio of the square root of the mean square value of the E.M.F.* to the value of the E.M.F. of a direct current machine. M is the total magnetic induction from one pole. Taw is the turns of armature wire per phase, n the revolutions per minute, and p the number of poles. The number of poles which the alternator must have is found from (2).

In the case of inductor alternators the foregoing formula applies, except that *half* the number of armature conductors per phase should be taken, and if of the double armature (Mordey inductor type), the number of conductors on one armature only should be taken. The flux given in (3) is the flux which must be interlinked with the armature conductors in order to produce the required E.M.F., the induction to be provided for in the field magnets must be greater than this, due to the loss from magnetic leakage, as all the field flux does not cut the armature wires; a certain proportion, depending upon the design of the machine, strays across from one pole to another and over the surface of the armature; this leakage increases slightly with the load, and also inversely as the power factor. The multiplier by which the armature flux has to be multiplied to get the field flux is termed the leakage coefficient, and is for alternate pole machines, whether with rotating field or rotating armature, from 1.15 to 1.4, and for inductor machines 1.4 to 1.7.

The formula (3) gives the E.M.F. generated in the armature due to Taw armature wires cutting a magnetic field of strength M, and may hereafter be described as the no-load terminal E.M.F. As soon as current begins to flow in the armature wires other factors seriously modify the voltage, and a considerable drop in pressure

* The mean height of a sine curve is .637 of its maximum height, while the square root of the mean square of all the ordinates would be .707. The effective value of an alternate current is defined as being equal to a steady current which produces the same amount of heat; this heating is proportional to the square of the current, hence the reason for taking root mean square values.

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may be observed, much more than can be accounted for by fall of pressure due to the armature current and armature resistance, which is equal to

$$e = Ca \times Ra \quad - - - - - - - - \quad (4),$$

generally termed ohmic drop, where e is the drop in volts, Ca is armature current, and Ra is armature resistance. The other factors which modify the terminal volts are self-induction and armature reaction.

As is well known, the first of these is due to the fact that in all electric circuits the passage of the current along a wire causes it to set up a field of its own, and any change in the magnitude or direction of the current is opposed, due to this field, as the current dies down or increases, inducing an E.M.F. which tends to maintain the current of the original magnitude and in the same direction. It will be apparent that this E.M.F., which will hereafter be designated es, is greatest when the change of the main current is greatest, that is, when the cycle of current is changing from + to − value. It therefore lags one quarter of a cycle behind the current which causes it, as will be seen from Fig. 13, where C is the wave of current flowing in the circuit, e s is the E.M.F. of self induction, which is displaced 90 degrees, a quarter of a complete cycle, from the current C : E is the resultant E.M.F. necessary to drive the current C through the circuit against not only the ohmic resistance, but also against the back E.M.F. of self induction, which as it is caused by the current must be proportional to it, so that other things remaining equal the greater the current, the greater the back E.M.F. of self induction.

It will also be apparent that this back E.M.F. is not added directly to the electromotive force necessary to overcome ohmic resistance, as it acts in quadrature to the current ; *i.e.*, assuming that the E.M.F. necessary to overcome the *ohmic* resistance is identical with C (it is absolutely in phase with it), it will be seen that the back E.M.F. of self induction is sometimes acting in the same direction, and sometimes in the opposite direction. This will be apparent from Fig. 13, where

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the E.M.F. of self induction es., and the E.M.F., E_1 necessary to overcome ohmic drop (in phase with C) are sometimes in the same direction, *i.e.*, simultaneously

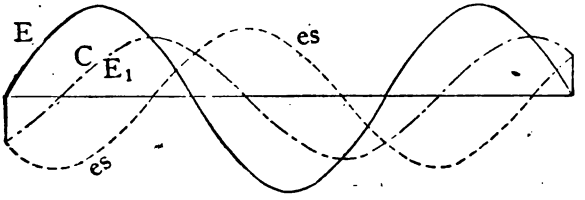

FIG. 13.

on the same side of the zero line, thus they are acting in unison, while at other parts of the cycle the E.M.F. to overcome ohmic drop is above the datum line. *i.e.* +, while the E.M.F., of self induction es. is — *i.e.*, below the datum line, and therefore opposing each other, consequently the impressed E.M.F., E, must at this instant be equal to the sum of the two other E.M.F.'s; while, when the two E.M.F.'s E_1 and ES. are +, the impressed E.M.F. need only be the difference between the two.

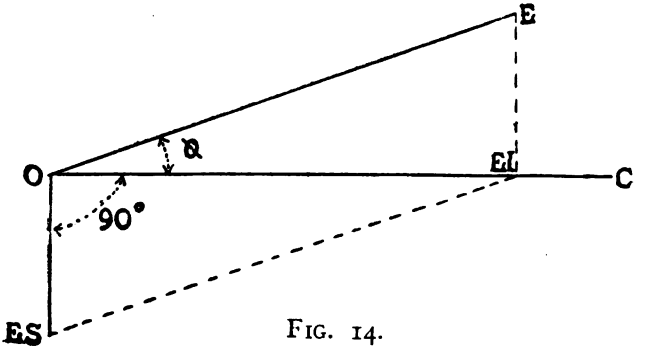

FIG. 14.

The most convenient way of showing the relation of the various E.M.F.'s is by the vector diagram, Fig. 14,

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where the current is represented by the vector O.C.; along this line is laid off to any convenient scale the E.M.F., O–E_1, necessary to maintain the current through the ohmic resistance. Lagging 90 degrees behind the current O.C. is the back E.M.F. of self-induction O–ES. By completing the parallelogram we get the line O—E, which represents the E.M.F. necessary to overcome ohmic drop and self-induction, and is the internal E.M.F. which has to be generated in the machine. The resulting current O-C lags behind the E.M.F. O-E by the angle ϕ in diagram 14, the cosine of which si the power factor of the circuit.

On measuring the instantaneous product of E and C, it will be found that so long as C is in phase with E, *i.e.* no lag, the power is a maximum, and in one direction only, but as soon as C begins to lag behind the impressed E.M.F., the instantaneous values of E × C become both + and —, and if C is displaced 90 degrees from E the product of these two values have equal + and negative values, and the resultant work which is the difference between the areas of the curves above and below the datum line would be O. This will be clear from Fig. 15, where A, B, and C represent, first, current in phase with the E.M.F., and consequently the instantaneous product (P) of E × C all + ; second (B) current lagging 65 degrees behind the impressed voltage and the power curve (P) partly + and partly —, while C represents the current 90 degrees behind the impressed E.M.F., and the power curve (P) of equal + and — value, hence the actual work done consists in circulating a current through the circuit, *i.e.* storing up energy in the coils of the inductive apparatus, then giving it out again. Of course, this last condition cannot be attained in practice, as there is always some energy required to overcome drop of pressure due to C × R loss (ohmic drop), as obviously current cannot pass through the circuit without loss of pressure and some work is therefore expended in overcoming this loss of pressure.

The same considerations apply to a circuit having capacity instead of inductance, the only difference

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being that the current *leads* the E.M.F. instead of lagging behind it. It is not difficult to understand the current lagging behind the E.M.F., but that the current leads

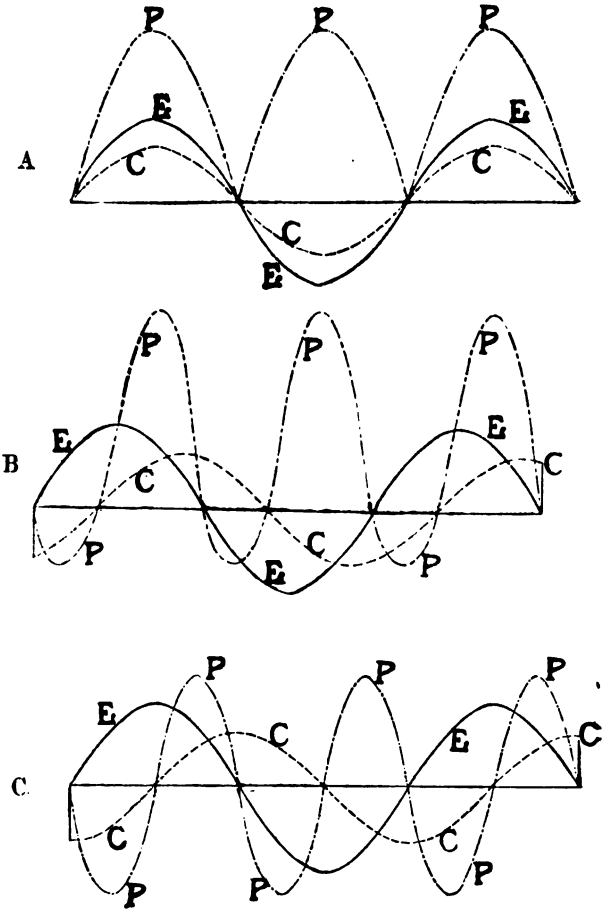

FIG. 15.

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the E.M.F. is taken as meaning that the current grows before the impressed E.M.F., an altogether impossible hypothesis; what really occurs is that when the E.M.F is first impressed upon the circuit, the current takes an appreciable time to reach full value, perhaps two or three cycles. During this time the current will grow from O to full virtual amperes, and as the current grows, so the effects of self-induction or capacity begin to assert themselves, and as the current grows towards normal value, it becomes displaced more and more from the E.M.F., this displacement being either ahead or behind the impressed volts depending on whether capacity or inductance is present. It should be noted here that capacity is often introduced into alternating current circuits to neutralise self-induction and *vice versa*.

It is a convenient hypothesis, and one largely adopted by continental writers to assume that there are two currents, one a watt component in phase with the E.M.F., and another a wattless component lagging 90 degrees behind the watt component. This is a convenient assumption when dealing with the armature reaction of alternators, and one which we shall use. As a matter of fact, it does not matter what hypothesis is introduced to explain this phenomenon, whether a current lagging behind the E.M.F., or two currents, one in phase with it, and another lagging behind it, the armature reaction can be satisfactorily explained.

The self-induction is proportional to the armature turns (in series), the current flowing in each turn, and the frequency of reversal. It is also influenced by the permeability of the surrounding medium, and as that medium is usually iron, which is for the most part at a high saturation, the permeability of its surroundings is not so great as might at first be imagined, it being obviously difficult to set up another magnetic field in a piece of iron which is already at or near saturation.

It has already been pointed out that alternators, if they are to have small drop of pressure between no-load and full-load, must have few turns of armature

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wire, and a very intense field, as any reduction of the armature turns necessitates a proportionate increase in the magnetic induction. This, however, obviously means a machine with heavy field magnets and large section of armature iron—in other words, more metal has to be put into the generator, so that good pressure regulation has to be paid for by increased capital cost.

The self-induction, as has been shown, depends upon the current, the number of turns, and the frequency of the change. If the field produced by unit current in one turn is denoted by m and the current is reversed $2 \frown$ times—*i.e.* number of changes or half waves, the maximum self-induced E.M.F. at the moment when the current passes across the zero line will be $2\pi \smile$ Cm for one turn, or for several turns $2\pi \smile$ cm Taw^2. The product of the two latter symbols is generally termed the coefficient of self-induction, and denoted by the letter L, it is generally expressed as the Henry, in honour of Professor Joseph Henry.

The self-induction of an armature may be measured by sending a current of known value through it at the pre-determined periodicity and the drop in volts measured, after deducting the loss due to resistance, the balance is E.M.F. lost due to self-induction, the actual E.M.F. of self-induction being

$$es = \sqrt{E^2 - E_1^2} \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad (5)$$

An example of the influence of self-induction in a three-phase alternator is given for illustration. A "Y" connected alternator designed for 5,000 line volts, or 2,900 phase volts, gives on open circuit 3,250 phase volts, on loading up with 20 amperes per phase the voltage fell to 2,900, due to ohmic drop, armature reaction and self-induction. Neglecting for the moment the second of these, and taking the resistance per phase as 5 ohms, we get 100 volts drop; therefore, 2,900 + 100 = 3,000 volts as E_1, Fig. 29, and 3,250 as E, the E.M.F. due to self-induction "es" must therefore be $\sqrt{3{,}250^2 - 3{,}000^2} =$

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1,240 volts, and the coefficient of self-induction of the armature.

$$= \frac{es}{2\pi \times \frown \times C} \quad - - - - - \quad (6)$$

$$= L = \frac{1{,}240,}{6{\cdot}283 \times 50 \times 20} = {\cdot}2 \text{ Henry}$$

The foregoing value is too high because the effect of armature reaction has been neglected. This tends to choke down the magnetic induction and so reduce the flux which is interlinked with the armature conductors. This reaction is modified by many disturbing factors such as the relation between the breadth of winding and the pole pitch, the nature of the load which the alternator is carrying, and so on.

The actual influence exerted by the armature can only be demonstrated mathematically, but it may be determined approximately. In most machines the back ampere turns are about 10 to 15 per cent. of the ampere turns on the armature, this, however, becomes very much greater if the generator is working on an inductive load.

Designers usually work back from the armature—*i.e.* the pressure regulation being known, they start by considering the limits imposed by the armature reaction. It is usual to take some such figure as ·25 for the value $\frac{At1}{At2}$, where At1 is armature ampere wires per pole, and At2 is field ampere turns per pole. Much depends upon the pressure regulation desired, ·25 is about right for a 5 per cent. drop between no-load and full-load (non-inductive), equal to about 12 to 15 per cent. at a power factor of ·85. The armature ampere wires may, however, be as high as ·3, or as low as ·22, depending upon whether the pressure regulation is required to be particularly good or otherwise, and also whether the power factor of the load handled be high or low. The ampere wires per pole found by this method must be kept below the upper limit of 300 ampere wires per inch of periphery, and if in preliminary calculations it is found that the value exceeds this, a reduction of the coefficient to say ·22 or even ·2 is desirable. As, however,

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...the ampere turns on the field required for the air gap is always so great that between 60 and 70 per cent. of the

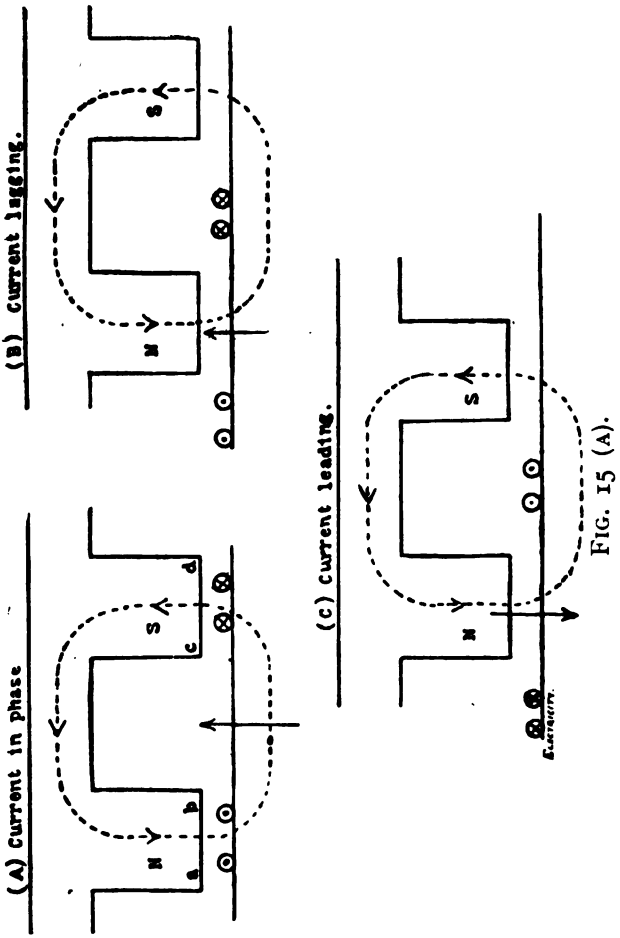

FIG. 15 (A).

total is for this purpose, it will be found that with the gaps used in current practice, the field ampere turns

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become so great that it is likely that the total ampere wires per pole will impose a limit before the foregoing ratios are exceeded.

At this point it will be desirable to give some explanation of the influence of lagging and leading currents on the pressure regulation of an alternator. As has already been pointed out with lagging current, the excitation must be increased very considerably, and must be much greater than the corresponding excitation with the same value of armature current at a power factor of unity. The reason is as follows: Take Fig. 15 (A) the diagram A represents two poles and two turns of the armature winding on one phase only. It is obvious that the magnetic induction due to the field magnets will follow the dotted line, and that the magnetic induction due to the armature winding will be in the direction indicated by the heavy arrow. The net result of an armature current at a power factor of unity will be that the poles at A and C will be strengthened, while that part of the pole at B and D will be weakened. This is exactly what happens with a continuous current machine, the leading pole horns being weakened and the trailing horns strengthened due to armature reaction. Turning now to diagram B it will be obvious that, as the wattless component of the armature current lags 90 degrees behind the watt component, the former will reach its maximum when the latter has reached the minimum. In other words, that the armature wires shown in A have passed to the position shown in B; the wattless component will then have reached its maximum, and as shown by the heavy arrow will be directly opposed to the field flux. Thus it is that for a given armature current, one having a power factor of ·8 will have a very much greater reaction and consequently require much higher magneto-motive force in the field coils than the other. A leading current on the other hand, such for instance as would be obtained if the alternator was feeding a long transmission line having capacity, or an over-excited synchronous motor, would strengthen the field. In this case the relative position

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of the armature coils and field magnet would be as shown in diagram C; here the wattless component reaches a maximum 90 degrees ahead of the watt component of the current, consequently the armature reaction would be as shown by the heavy arrows in a direction which would assist the magnetic induction due to the fields. Thus it is that when an alternator with fixed excitation is working on an inductive load, its terminal E.M.F. falls, whereas when working on a load having capacity—*i.e.* leading current, its terminal E.M.F. rises, the armature moving from left to right in each case.

CHAPTER VI.

Armature Windings.

We have considered the basic principles of the alternator, and will now deal with the details of construction, first of which comes the armature and its windings. As will be seen from Figs. 2

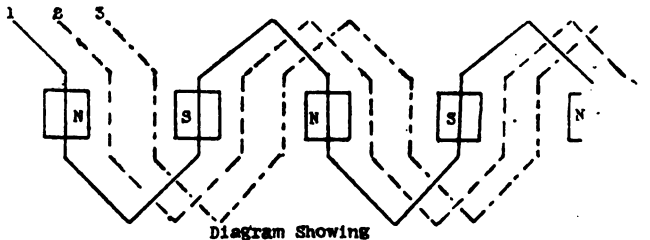

Diagram Showing
3 phase 1 slot per pole & phase or uni tooth, winding
Wave winding.

Fig. 16.

and 3, the essential difference between two and three phase machines consists only in the disposition and number of groups of armature conductors in their relation to the field coils. The simplest winding of this kind would be a machine as shown in Fig. 16, having one slot per pole and phase; comparatively few machines

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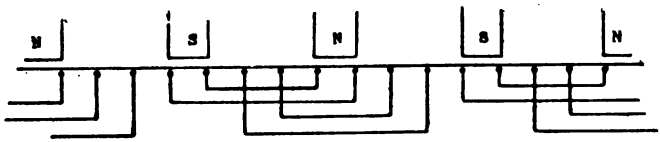
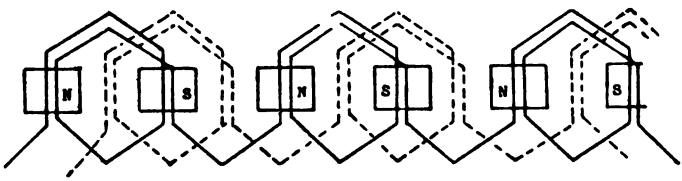
of this type are now built because of their bad regulation, engineers, especially in England, demanding a small drop of the order of 3 to 8 per cent. with unity power factor, while this type has a drop of about 12 to 14 per cent.; moreover, such alternators generally give a wave form which bears little resemblance to a sine curve,



2 phase, 2 slots per pole and phase

FIG. 17.

hence does not work well in parallel with others of a more conventional design, and if synchronous motors are used on any part of the circuit which may be made by some other firm, and give an E.M.F. more or less closely resembling a sine curve, the results would be unsatisfactory. On the other hand such uni-tooth alternators are very safe machines when short circuited, the current or short circuit does not often rise above



2 phase, 2 slots per pole and phase.
Lap winding.

FIG. 18.

twice the full-load current. They are sometimes built compounded, and as such are pretty satisfactory.

More general windings are shown in Figs. 11, 17, and 18; these show two- and three-phase windings, having 1, 2 and 3 slots per pole and phase. The more

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uniform distribution of the conductors over the face of the armature in several slots per pole and phase, decreases the self-induction of the winding, and therefore results in better regulation, while the core surface is better utilised, and a more even heating of the windings is obtained. Of course it precludes the use of machine wound coils, and therefore makes the cost of winding greater, but with large alternators the labour charge on this item does not exercise any serious influence on its final cost. It is more easy to insulate uni-tooth alternators, and that is one reason for the decreasing number of slots with high tension armatures. Another consideration is that the E.M.F. per yard of armature wire

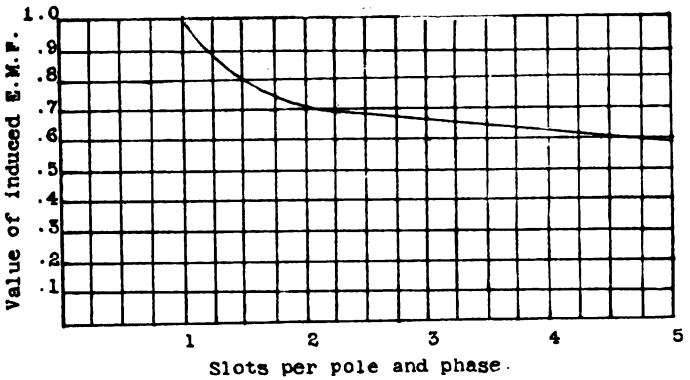

FIG. 19.

is slightly less with multi-tooth armatures; this is not very serious, though it is a point which must not be lost sight of in designing, as it is more apparent at no-load than at full-load. Fig. 19 shows the relative E.M.F. for a fixed number of turns or armature wire per phase when concentrated in one or scattered in two, three, or four slots per pole and phase. It will be seen that although for a given weight (or length) of armature copper a higher E.M.F. can be obtained with uni-tooth winding, or what amounts to the same thing less copper

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is necessary to produce a given E.M.F. with the winding concentrated in one slot per pole and phase than with it scattered in several; this advantage disappears as the machine is loaded up, the additional reaction of the concentrated winding more than offsets the advantage which it seems to possess at no-load.

There is no uniformity as to the number of slots per pole and phase, but from a number of machines by different makers, English, European and American, it would appear that practice tends towards three to four slots per pole and phase up to 2,000 volts; though three slots are most usual, between 3,000 and 5,000 volts two slots are common, and one slot only is not infrequently found, while over 5,000 volts the use of one slot only is pretty general.*

The slots are generally punched in the core, but sometimes milled; this, though apparently a more expensive process, does not really exert a very great influence on the total cost, as even when the slots are punched they are often cleaned out by a milling cutter. Fig. 20 shows the various slots and holes generally used in modern alternators. The use of closed or partially closed slots, Nos. 5 to 10, makes the use of former wound coils impracticable, and as a general rule it may be said that on the Continent, where labour is comparatively cheap, closed or partially closed slots are common, while in the United States and in Great Britain, where labour is more costly, open slots, that is, slots with the mouth as wide as the remainder of the slot, are employed for the purpose of enabling former wound coils to be used. At the Paris Exhibition of 1900 hole wound armatures predominated, though in most cases there was a narrow slot across the thinnest part of the iron to reduce magnetic leakage by interposing a

* In the case of the 5,000 K.V.A. three-phase alternators in the Moabit Power Station, Berlin, there are five slots per pole and phase; the diameter of the armature which is fixed is 24 feet 3 inches; the E.M.F. is 6,000 volts. The 3,000 K.V.A. 10,000 volt two-phase alternators in the Willesden Station of the Metropolitan Electric Supply Co., London, have three slots per pole and phase; the diameter of the armature is 25 feet.

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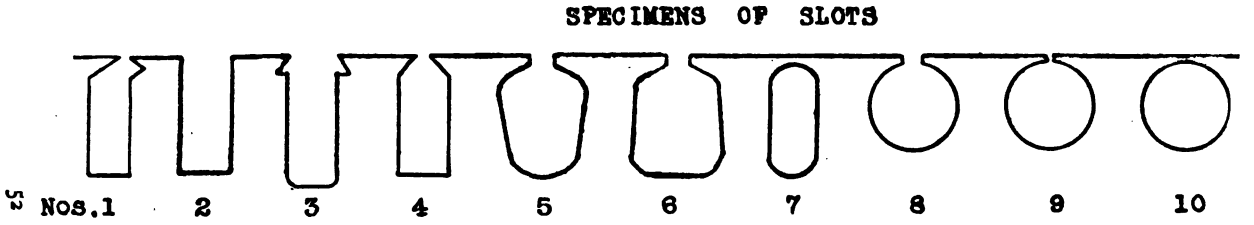

Nos. 1, 3 and 4 are always, and Nos. 5 and 6, generally filled with a hard wood wedge after winding.

FIG. 20.

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short air-gap into the leakage path, as shown in Fig. 20 No. 9. One advantage of the closed slot is that it obviates the necessity of laminating the pole faces; it also reduces the magnetic reluctance of the air gap. On the other hand, it increases the self-induction of the windings, and thus, given other factors equal, such an armature is rather poor in regulation.*

It has already been shown (Fig. 19) that multi-slot winding tends to slightly increase the amount of armature copper for a given terminal E.M.F. at no-load, but, on the other hand, the increased armature reaction and self-induction of uni-slot (or tooth) windings more than counterbalance this difference, as the machine becomes loaded up towards full-load. Multi-slot windings utilise the available winding space on the periphery of the armature more effectively, and, *inter alia*, bring about a more equal distribution of the heating of the windings and core. Machines having windings spread out give a wave of E.M.F. more nearly resembling the ideal sine curve; the method of winding thus influences the shape of the wave of E.M.F. to a considerable extent, and frequently determines the number of slots per pole and phase. One or two slots per pole and phase is general for high tension machines, as to distribute the windings in a greater number of slots means that a relatively larger amount of core-space must be devoted to slot insulation.

The armature windings of two- and three-phase alternators are in the case of two-phase generally so grouped as to have the two phases, at any rate, distinct up to the terminals of the machine, while after that it is common practice to join two ends to a common wire, the current being then $\sqrt{2} \times x$. Where x is the amperes in the outer wire, this results in a saving of copper so far as distribution is concerned, the feeders and distributors, consisting of two wires of x section and one of $x \times \sqrt{2}$; whereas with a common four-wire two-phase system the four wires are all of the same section. The

* The regulation of one or other type is, however, influenced by other and more important considerations.

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Midland Electric Power Corporation, who supply power over a large area in Staffordshire, distribute on a two-phase three-wire system, so also do Sheffield Corporation. It may be remarked in passing that two-phase three-wire systems differ from direct current three-wire systems in that the third wire is *larger* in section than its neighbours, having to carry the vectorial *sum* of two currents differing by 90 degrees, whereas in the case of a three-wired direct current the middle wire is *smaller*, having to

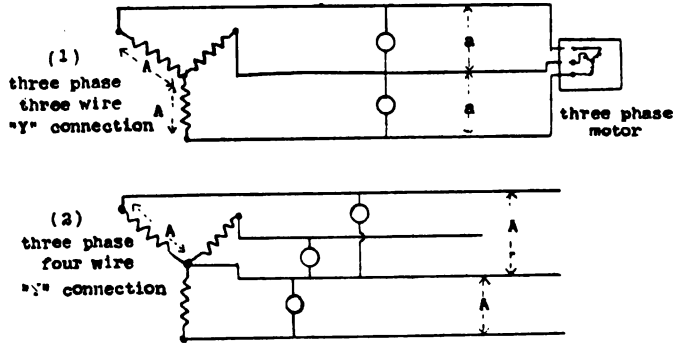

FIG. 21.

carry only the *difference* between the current on one or other side.

In three-phase working we may have the generator windings connected either in star or delta, the former with three or four wires, and the latter with three only, though a delta-connected generator may supply through

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transformers giving star connection on the secondary side, or an artificial neutral point may be established outside the generator on a pure delta-connected system. The various methods of connection are shown in Figs. 21 and 22, while the corresponding values of E.M.F. and current are given in Table IV., where A and *a* are phase and line *volts*, B and *b* phase and line *amperes* respectively. Line amperes meaning of course amperes per wire, except in the case of the two-phase three-wire system, where the common return has greater current.

TABLE *IV.*

System.	Phase Volts.	Line Volts.	Phase Amperes.	Line Amperes.
2-phase 4-wire	A	$A = a$	B	$B = b$
2-phase 3-wire	A	$A \times \sqrt{2} = a$	B	$B = b$ in outers $B \times \sqrt{2} = b$ in common return.
3-phase Y 3-wire	A	$A \times \sqrt{3} = a$	B	$B = b$
3-phase Y 4-wire	A	$A \times \sqrt{3} = a$	B	$B = b$
3-phase ∇ 3-wire	A	$A = a$	B	$B \times \sqrt{3} = b$

It has frequently been said that three-phase delta connection is more extravagant in line copper than three-phase star connection, and the above table would appear to justify this impression. This, however, is founded on a misapprehension, for, taking the same *line* voltage in each case, exactly the same amount of line copper is required. The phase voltage of a three-phase alternator is, however, in the case of a delta-connected machine, the same as the line volts while the current in each phase is less than the line current, the latter being the vectorial sum of three currents differing by 120 degrees; thus a three-phase alternator if delta-connected will have a line voltage of the same magnitude as the

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phase volts, and the line current—*i.e.* amperes per wire output, will be $\sqrt{3}$ times the phase amperes, while with a star-connected alternator the line voltage is greater than the phase voltage, as shown in Table IV. It is apparent, therefore, that to get the same line volts and line amperes in either case the delta-connected alternator must have a *greater* number of turns per phase than the star-connected machine in the ratio of $\sqrt{3}$ to 1; on the other hand, the sectional area of the wire on each phase of the delta-connected machine is

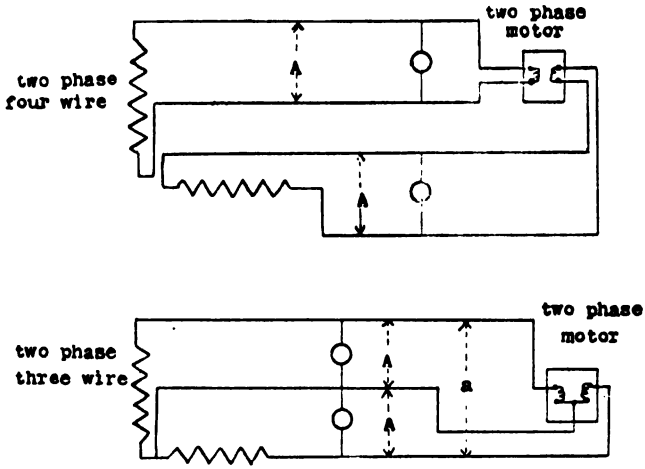

FIG. 22.

smaller than that of a star-connected machine by exactly the same ratio, so that, taking similar *line* volts, the amount of copper required does not differ.

It may be noted here that the usual current densities in the case of fixed armatures is from 1,000 to 1,500 amperes per square inch, and in the case of rotating armatures from 1,500 to 2,000 amperes. Disc armatures which, being non-slotted and having a much larger amount of coil surface exposed to the cooling influence of the air, are sometimes worked up to 3,500 amperes per

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square inch. These disc machines by reason of their low self-induction, &c., are not much used in modern polyphase plants, but they have done excellent service in many single-phase stations all over the country. The only other point influencing the design is the stress on the insulation ; this is greatest with mesh or delta-connected generators by about 73 per cent. In the case of a star- or Y-connected machine with the middle of the Y earthed, as is usual, the voltage to earth is only the phase voltage, which, as we have already seen, is less than the line voltage by more than 40 per cent. In the case of delta-connected machines the phase volts and line volts being the same, the insulation stress is equal to the full voltage of the machine.

CHAPTER VII.

Mechanical Construction of the Armature.

The mechanical construction of the armature is a point of considerable importance, particularly in the case of large generators, where not only the usual magnetic strains have to be provided for, but the tendency of the structure to deformation due to its own weight has to be considered.

When the armature reaches a diameter of 3 or 4 feet it is general to build it up of segments instead of circular plates, while if the machine is of the rotating field type, this method of construction is general. Circular and segmental core plates for rotating field machines are shown in Figs. 23 and 24.

Revolving armatures are now confined to comparatively small alternators ; there are a few exceptions, chiefly American, but it may be said that, generally, all alternators are of the rotating field type. The construction of the armature, if of large diameter, under these conditions involves many considerations. One method which is adopted with slight modifications by Brown Boveri, Lahmeyer, Compagnie International

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d'Electricité, and a few others, is to carry the armature in a cast-iron frame, which is stiffened by radial cast-iron arms terminating in a circular boss, as shown in Fig. 25. This gives a structure which, while heavy and extravagant in material, is stable to a degree which cannot be excelled; a lighter modification is that shown

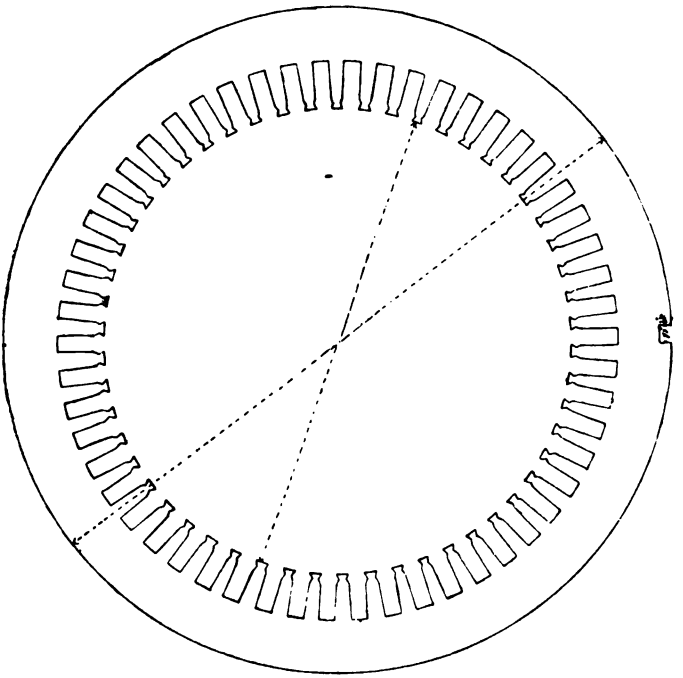

FIG. 23.

at the Paris Exhibition by the Schuckert Co., and the Compagnie Générale Electrique of Nancy; the circular yoke remains unaltered, but tie-rods or circular section are brought down to an iron ring concentric with the shaft, but some distance from it, as shown in Fig. 26. A still lighter armature is the tie-rod construction of

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the Allgemeine Elektricitats Gesellschaft, Berlin (The Electrical Co., London), one form of which is shown in

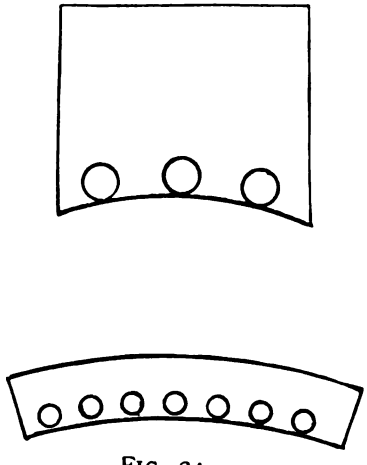

FIG 24.

Fig. 27, and another similar to that adopted for the stiffening of the armature frame of the 4,250 k.w. three-

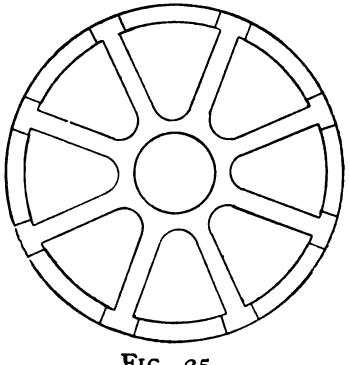

FIG. 25.

phase generators at Manchester, and the 5,000 k.w. three-phase generators in the Moabit and Oberspree

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Power Stations, Berlin, is shown in Fig. 28. In these tie-rod constructions the cast-iron frame is practically dispensed with, and only two wrought or cast-iron cheeks are used, between which the laminations are assembled; the whole is tightened by means of bolts passing through

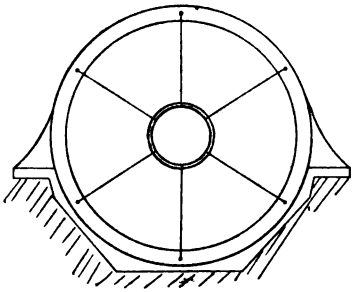

FIG. 26.

from one cheek to another, and the armature, after assembly, is braced by the tie-rods in the manner shown. This construction makes the structure lighter, and therefore less costly to handle. The great difference is clearly

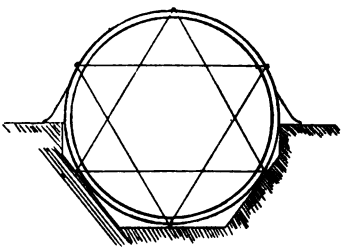

FIG. 27.

shown by the fact that the armatures of the 3,000 k.w. three-phase alternators in the Moabit and Oberspree stations weigh 67 tons, with a cast-iron U-shape frame, while the 5,000 k.w. alternators in the same stations, having braced armatures, weigh only 40 tons—*i.e.* an

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increase of 65 per cent. in output, with a decrease in weight of 40 per cent. Notwithstanding all that can be said in favour of specially braced armatures, there has been no very general increase in this method of construction, and on the Continent, in the United States,

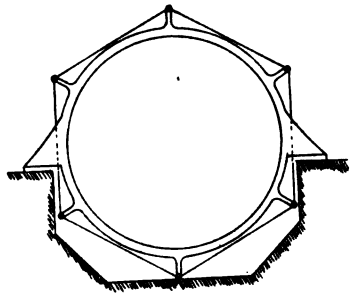

FIG. 28.

and in Great Britain, most constructors favour some cast-iron or steel structure of U-shape box section to give the requisite stiffness to the armature, although with slow speed engines and armatures which have

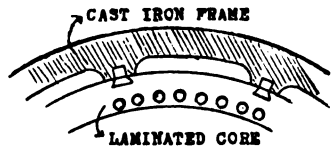

FIG. 29.

an internal diameter of over 20 feet, the use of a steel frame in tension would appear more reasonable, and certainly more like good engineering than a cast-iron structure of perhaps double the weight. Should the use of slow engine speeds prevail, which is possible if the large gas engine develops along present day lines, it is probable that stress of competition may demand a departure from the cast-iron armature frames of to-day,

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just as the use of light steel frames has superseded cast iron in all other kinds of structural work.

Up to the present the great majority of firms build armatures with a cast-iron frame heavy enough to give the necessary stiffness to the structure ; among these may be mentioned Kolben and Co., Prague ; Electricité et Hydraulique, Charleroi ; Schneider and Co., Creusot ; British Thomson Houston Co., Westinghouse Co.—the latter, however, build many machines with *rotating* armatures and fixed field magnets carried in such a frame ; Bruce Peebles (Ganz), Electric Construction Co., and others. It may be noticed in passing that the Lahmeyer Co.

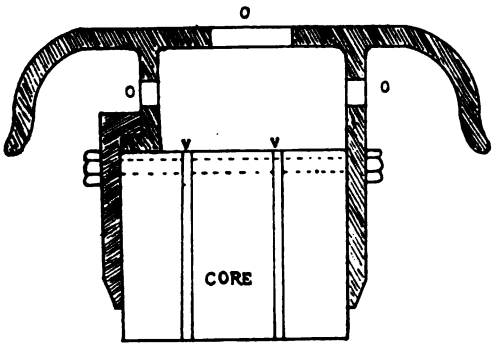

FIG. 30.

exhibited an alternator of this type having a capacity of 2,000 k.w. at Dusseldorf Exhibition, 1902, while at the Paris Exhibition of 1900, their 1,000 k.w. alternator had the armatures stiffened as shown in Fig. 25.

A section of Fig. 29 shows one method of fixing the core plates in the cast-iron frame ; this particular construction is by the Helios Co., but all others differ only in detail, as will be seen from a reference to Figs. 30 and 31. These latter are cross sections of the armature cut across parallel to the shaft of the machine, while Fig. 29 is cut at right angles to the shaft—*i.e.* it is as if the machine were looked at from

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the end of the shaft. Figs. 30 and 31, are good examples of modern construction with the core plates carried by a cast-iron frame; nearly all the leading firms adopt some such method of construction, differing only in details such as the shape and arrangement of the frame and its ventilating openings O. The ducts V are to permit of

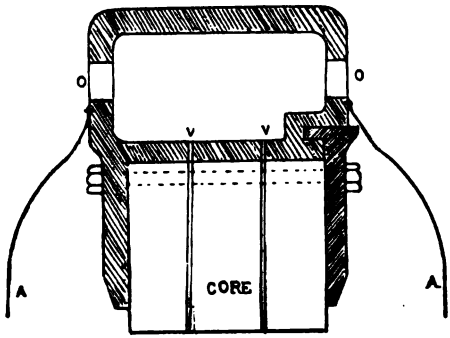

FIG. 31.

ventilation of the armature core. While the lines A in Fig. 31 are for the purpose of affording some mechanical protection to the ends of the windings, and are generally of some non-magnetic material. Illustrations of the armature frames will be seen among the complete machines, Chapter XVI.

CHAPTER VIII.

THE FIELD MAGNET SYSTEM.

The design of the field magnet involves not a few considerations, electrical, mechanical, and magnetic. One important difference between direct and alternate current generator design is the predominance of rotating field magnets; with few exceptions builders adopt rotating fields, the exceptions are generally

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small machines, though a few large low tension alternators have fixed fields and rotating armatures, one example being the 1,500 k.w. Westinghouse two-phase alternators at the Willesden station of the Metropolitan Electric Supply Co. These generate at only 500 volts per phase, while the Kolben alternators of 3,000 k.w. in the same station have a voltage of 10,000 per phase, and a fixed armature. The principal reason for having a fixed armature is that with high pressures it is obviously desirable to have the part subjected to high tension fixed, as good insulation is more easily obtained, and it is subjected to fewer mechanical strains, indeed, the armature is in many respects as simple as a transformer.

The method of fixing the magnets which are often laminated, must necessarily be mechanically strong, as the usual velocities are 4,000 to 6,000 feet per minute, and even this figure is sometimes exceeded. The former for alternators with cast-iron magnet wheels, and the latter cast steel. The pole or pole faces are laminated, chiefly on account of the variations of the magnetic flux, due to the teeth or the slot passing the pole face. It may be said that the eddy currents in the pole faces due to the foregoing variations are dependent upon the relative width of tooth and slot, and also the relative width of the slot and length of air gap. With hole wound alternators, laminating even the pole face is unnecessary as there are no important variations in the strength of the field.

Laminated fields enable somewhat higher flux densities to be employed, therefore lighter machines, and with high flux density the field is less likely to be influenced by armature reaction, though when operating on circuits of low power factor, and under similar circumstances where any increase in induction is desirable, such increase can only be obtained, if at all, at the expense of an enormous amount of exciting current, hence it is well not to push the induction too far.

Current densities of 1,300 to 1,900 amperes per square inch may be used, as owing to the fact that the bobbins

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rotate the cooling effect is considerable, if, however, fixed field magnets are employed the current density is never greater than 750 to 1,000 amperes per square inch. Round wire should never be employed except for small machines as the stresses due to centrifugal force cause the wires to chafe on each other and destroy the insulation ; copper strip wound on edge with insulation wound on with each turn is frequently used, and answers well, as the tendency of the centrifugal force is simply to compress the flat sides of the spiral together. Round poles are most economical in field copper, but as it is not easy to make them laminated they are not often used, though oval poles which are more economical in this respect than rectangular poles, are often used in conjunction with laminated pole faces. In order to reduce the magnetic leakage from pole to pole, very short poles

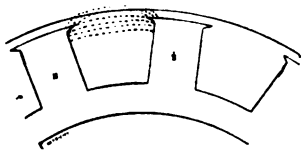

FIG. 32.

with deep winding are sometimes used. Apart from the fact that this is extravagant in field copper, due to the greater length of a mean turn, the temperature of the inner layers is always high.

A source of leakage field is leakage from pole horn to pole horn. The pole pitch of most alternators is shorter than usual in direct current practice so that the horns come closer together, hence the resistance of this leakage path is, comparatively speaking, small. The path of the leakage flux may be more easily seen from Fig. 32, where two poles are shown, and the various leakage paths are shown dotted. Fig. 33 also shows the leakage paths of an inductor alternator, where it will be seen that part of the leakage is from the root of the pole—*i.e.* the yoke. With closed or partially closed slots there is always a small leakage of field from

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pole to pole across the surface of the armature*, therefore although the field actually reaches the armature core, it does not link with the armature conductors, this is one reason why open slots are employed, and, even where

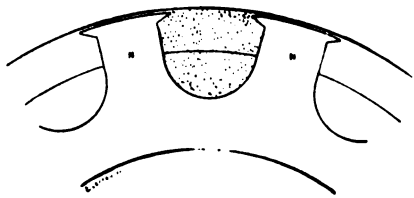

FIG. 33.

closed slots are preferred, they are generally slit across the thinnest part of the iron, thus introducing several short air gaps, which somewhat reduces the leakage at this part. In the case of inductor alternators, the leakage from the

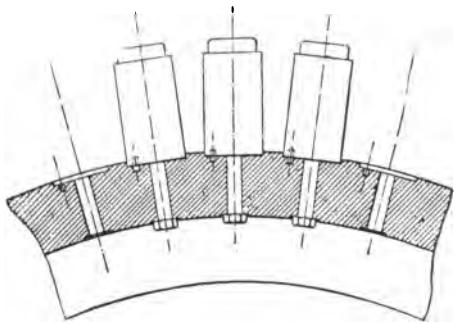

FIG. 34.

inductor across the part between the poles sets up an E.M.F., which may be at the moment actually opposing the main E.M.F., induced in the armature conductors,

* Owing to the high density of the flux in this part it is not, in some alternators, a serious loss, as the saturation is carried so far that the magnetic reluctance of this path is little short of air itself.

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so that it is much more serious than might at first sight appear.

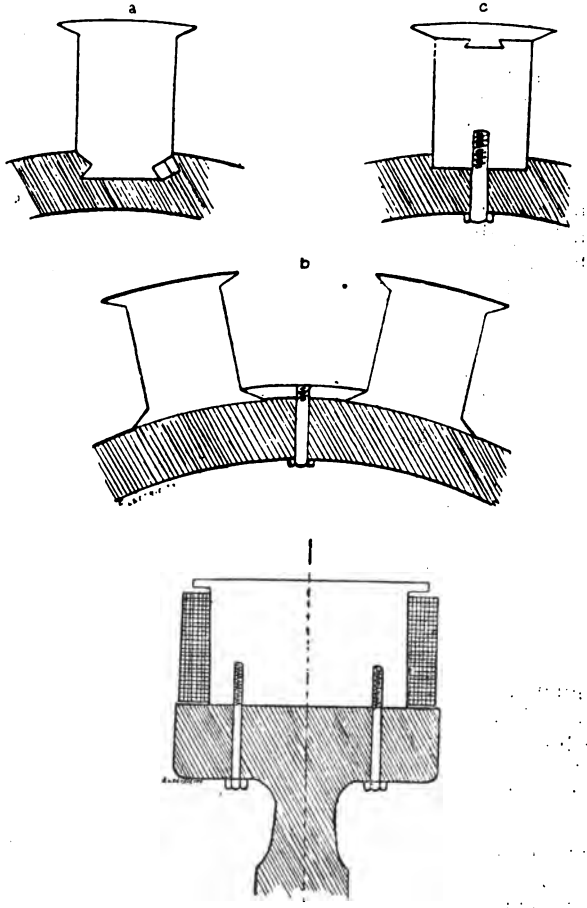

FIG. 35.

The amount of the field induction must, in order that the proper flux may be interlinked with the armature con-

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ductors, be increased by a considerable amount as it is now clear that all the field magnet flux is not usefully employed. The leakage coefficient, or the figure by which the flux found by calculation as necessary to produce a given E.M.F. must be multiplied in order to get the actual field flux, is from 1·3 to 1·6 for alternate pole alternators, and 1·4 to 1·75 for inductor alternators. Knowing the total flux, the sectional area of the magnet cores, and the rim of the magnet wheel, where the latter forms part of the magnetic circuit, can be determined from the values given in Table III.

One method of fixing the magnet core to the rotating wheel is shown in Fig. 34, which is a section of the

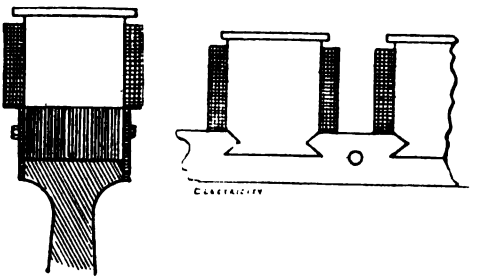

FIG. 36.

magnet wheel of the 1,760 k.w. Brown Boveri three-phase alternator at the Paris Exhibition of 1900. This method is adopted with very little modification by many of the leading builders of alternators. The Allgemeine Elektricitats Gesellschaft adopt one method of keying the poles as shown at "a," Fig. 35; this method is adopted where laminated poles are keyed to a cast steel magnet wheel, and is very efficient when the surfaces are well machined to reduce the magnetic reluctance of the point. Another of this firm's designs is shown, Fig. 36, where not only the magnet cores, but the yokes are laminated, the laminations which form the yoke being held together by wrought or cast iron plates on either side, secured

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by bolts passing through from side to side as shown in the section.

Fig. 35, " b,"shows another method of fixing the laminated field pole, used sometimes by the Oerlikon Co., who, however, often fix the poles as in Fig. 34. In same figure, " c " illustrates a method of fixing the pole to the magnet wheel, where the pole is solid, and has a laminated pole face to which the steel pole is cast. Sometimes the laminated face, instead of being fixed when casting the pole, is held by screws or bolts passing through the laminations as shown in Fig. 37 ; " d " is the extreme where neither laminated poles nor even pole faces are used, it is a standard construction of the Electricité et Hydraulique Co., of Charleroi, and is quite permissible

FIG. 37.

where tunnel windings are used, the tunnels per pole and phase being fairly numerous, say three or more, though the writer has seen them employed with only two tunnels, even then there were apparently only very small eddy currents in the pole horns as these were cool ; " a," " b," and " c " of Fig. 35 and also Fig. 37 are views looking from the shaft end—*i.e.* parallel to the shaft, while Fig. 35 " d " is looking at right angles to it. Another construction differing from all the foregoing is one by the Westinghouse Co., for the magnets of medium-sized machines, and consists of stampings shaped as shown, Fig. 38. It will be seen that each stamping consists of one complete pole with half of each adjacent pole, these are dovetailed into the spider as

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shown. The stampings are so arranged that the joints of one layer come opposite the complete pole of the next. It will be seen that, although the poles cannot be removed and repairs can only be effected by racking the armature clear of the field, yet other advantages are secured, for instance the whole field circuit while laminated, contains no joints in the path of the flux, and is therefore superior to the A.E.G. construction, shown Fig. 36, where a complete laminated magnetic circuit is also obtained but with joints directly in the path of the flux. Moreover, the absence of joints at a point where the strains due to centrifugal force are great, cannot fail to convey the impression of mechanical strength. It is worthy of note that this method of securing the field stampings to the spider is similar to the

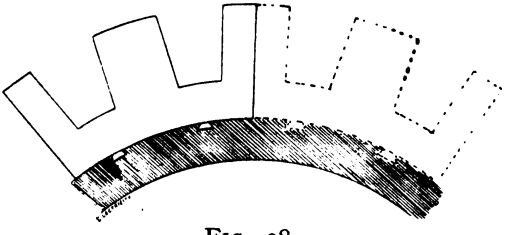

FIG. 38.

Helios method of securing the armature stampings to the armature frame, see Fig. 29.

In designing the magnet system the designer generally bears in mind the fact that it may be necessary to remove the poles or get the magnets clear of the armature in order to repair either a magnet winding, or more likely an armature coil; one method, and a not uncommon one with makers of fairly high speed alternators, of relatively small diameter, is to so arrange the bedplate that the fixed armature may be racked to the side leaving the field standing in its bearings in the original position, while the armature is moved to the position shown dotted, Fig. 39; of course this practice is not confined exclusively to machines of small diameter, several

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continental firms have made machines of large diameter so arranged. It will be apparent, however, that any means whereby the field poles can be removed laterally, entirely eliminates the necessity for racking the whole armature. For instance, the removal of the cotters. Fig. 35 (a) will enable the field pole to be easily removed and replaced. To rewind an armature section, it is a

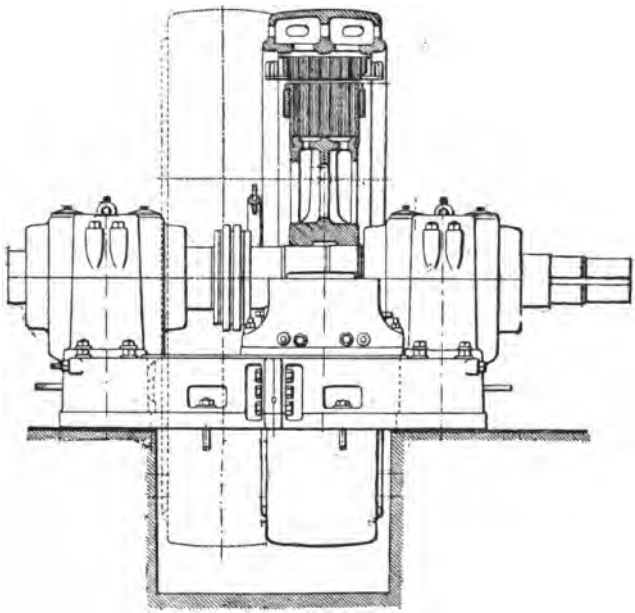

FIG. 39.

matter of no difficulty to remove two, or at most three. adjacent poles in order to enable the winder to work under satisfactory working conditions. With machines designed as in Fig. 25, where the armature is carried by radial castings which terminate in a central hub, this hub is often arranged so that the armature may be racked round its hub, in order to bring those portions

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above or below the floor level, within easy reach of any one working on the floor. Some such arrangement is much more desirable than sliding the armature laterally, particularly where the alternator is fixed between the cranks of the driving engine, the distance between the bearings, and also the floor space taken up by the plant is less. When the armature is arranged to slide on its sole plate, the distance between the cranks of the engine must be greater to permit of this being done—though generally this arrangement is confined to alternators driven by high speed engines, where the engine is at one end only.

CHAPTER IX.

Magnet Windings.

The next point is to determine the amount of copper necessary on the magnets. The total ampere turns required must be found, and from that the amount of copper on each field bobbin is easily determined. The ampere turns necessary for the field and armature system may be found from Fig. 6, once the length of the magnetic path and the density of the induction in the magnet core, yoke, teeth, and armature body are known. The only point requiring determination is the ampere turns required to force the necessary induction across each air gap. This is

$$\cdot 313 \times l \times 2 \times d. \quad .. \quad .. \quad .. \quad (7)$$

Where "l" is the length of *one* air gap in inches and "d" is the density of the magnetic induction per square inch, the factor 2 is introduced as there are in a complete magnetic circuit two air gaps. It is usual, however, to calculate the ampere turns *per pole* taking for this purpose that part of the magnetic circuit embraced by the shaded portion, Fig. 40, in which case the factor 2 is eliminated, there being for each pole winding only one air gap. The total number of ampere turns per pole now being known the

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proper gauge and length of wire has to be determined; this is found by several more or less empirical formulas, but the process of fixing this will be described first from elementary principles, and secondly by an empirical method giving rapid yet accurate results.

First fix the difference of potential per pole by dividing the E.M.F. of the exciter by the number of poles; the result is often as low as $2\frac{1}{2}$ volts in the case of a 40-pole machine with a 100 volt exciter. The practice is in many stations to excite the alternators at 220 volts or thereby, using steam driven sets which also do other work, such as supplying current to the motors driving auxiliary station machinery or station lighting. Hence the figure of $2\frac{1}{2}$ volts is probably the lowest figure, 5 or 8 volts being likely under such circumstances. The watts available for excitation purposes being determined

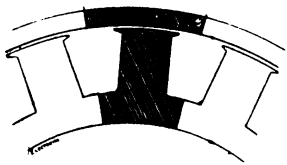

FIG. 40.

from considerations of efficiency and temperature limit, the amperes necessary can then be found; this divided into the ampere turns per pole gives total turns per pole. From a drawing of the machine take the approximate mean length per turn, this multiplied by the total turns per pole gives the length of wire on each pole. It will be seen that we are now in possession of three factors. First, the difference of potential at the terminals of each coil; second, the amperes under normal conditions; third, the length of wire on each pole. We now find the resistance per pole from the known current and E.M.F. This is the last link, as all that is now necessary is to find the gauge of wire which will give the required resistance and length. This is easily found by proportion, care being taken to figure the result on a basis of wire at

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a temperature approximately equal to that of the coil under working conditions.*

Another and more rapid method is by the use of the curves Fig. 41. These curves are from an article contributed to the *Electrical Engineer* of New York some years ago, by J. P. Stone†, and the writer has since then frequently employed them with very satisfactory results.

The diameter of the bare wire in mils (thousandths of an inch) is found from the formula—

$$\sqrt{\frac{AT \times b}{V}} \quad .. \quad .. \quad (8)$$

Where AT = ampere turns per pole, b is mean length of one turn, and V is difference of potential across each bobbin. The results are, however, only accurate for round wire. In the case of rectangular wire, which, as has already been pointed out, is commonly employed for the exciting coils of rotating field alternators, the sectional area corresponding to the diameter obtained by the foregoing formula must be taken, while owing to its more economical section about 10 per cent. more turns per square inch can be got into a coil with a corresponding increase in the amount of copper in the coil. Allowance has been made for imperfect winding and the waste space resulting therefrom. If the figures giving the percentage copper in the coil be multiplied by ·0032 the weight in pounds of the copper is obtained, a useful figure in calculating the cost.

When these windings are being calculated the necessity for considerable increase in the excitation to enable the machine to maintain full voltage on circuits of low power factor, or when carrying overloads, must be reckoned with. This has already been noted at the close of the section on armatures ; from which it will be evident that circumstances may demand considerable increase. As an instance, an alternator carrying a 50 per cent. overload on a circuit having a power factor of ·85 may require as much as 30 per cent. increase in the exciting

* The resistance of copper increases about 0.21 per cent. per degree Fahr., or .38 per cent. per degree C.

† *Electrical Engineer* (New York), vol. 25, page 318.

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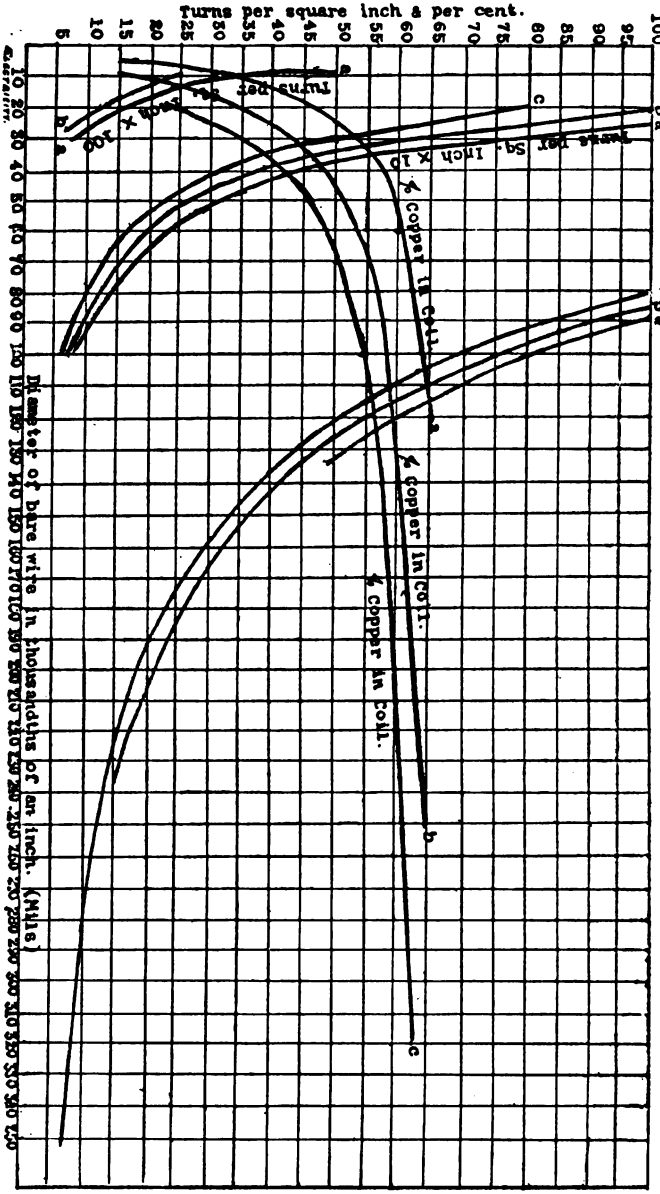
Turns per square inch & per cent.
Turns per Sq. Inch x 10
% Copper in Coil.
% copper in coil.
% copper in coil.
Diameter of bare wire in thousandths of an inch. (Mils)

FIG. 41.

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current, but this amount will vary within wide limits, depending on the saturation of the magnetic circuit.

CHAPTER X.

Methods of Excitation and Compounding.

The most usual method of excitation is by means of a small direct current generator, either directly coupled or belted to the main generating unit. This has several disadvantages which those operating the plant soon discover. A sudden overload tends to pull up the alternator and naturally its voltage falls off, due to the reduction in speed and to increased armature copper loss; the reduction in speed also affects the direct or belt-driven exciter, with the result that its voltage drops off too. Thus not only is the terminal E.M.F. of the alternator reduced by the drop in speed, but the E.M.F. of the exciter is also reduced just at the time when it is most important that it should be maintained at full value. A reduction in speed therefore has a cumulative effect on the electro-motive force of an alternator with its own exciter, which, under certain circumstances is decidedly disadvantageous, hence other methods of excitation are generally employed where the plant is sufficiently large, the most usual being separate engine-driven sets, such as a high speed engine and direct current dynamo which feed on to a pair of exciter bus bars; from the latter the alternator fields are excited. By this means an alteration of the exciter field regulator varying, as it would, the E.M.F. of the exciting current, would strengthen or weaken the excitation of *all* the alternators excited from that particular unit, an important consideration in parallel working. Adjustment of the field of individual alternators can be effected by means of the resistance in series with the field of that machine.

There are, in addition, several methods of self-exciting and compounding. One of the first practical

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compounded machines with which the author is familiar was made by the General Electric Co., U.S.A., about nine years ago, and in some respects, though in a somewhat crude manner, anticipated Heyland's latest machine. Fig. 42 shows the general arrangement of the armature and its connections. It will be seen that an ordinary star connected generator is employed, but instead of connecting the inner ends directly to each other they are connected to three commutator segments,

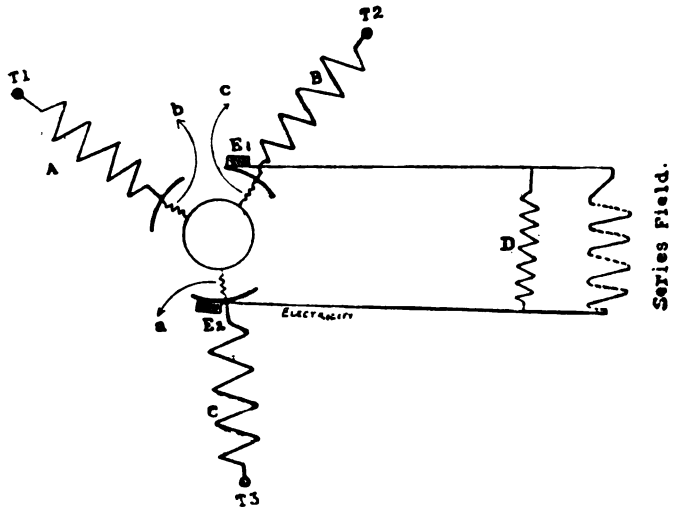

FIG. 42.

which are shunted by low resistance shunts terminating in a ring, so that at or near full load there is a difference of a few volts between the segments owing to the drop of pressure over the shunts a, b, and c. It is obvious that with such a winding the direction of the current in the phase which is opposite the top segment will always be the same, and therefore a uni-directional current will flow from the brush " E1 " through the series field and shunt d to E2. It must be kept in mind that if E1 is

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+ to E2, as will be the case in this instance, the current in B will be at a — maximum at this particular instant, and will be passing out through A and C, and returning through B. In other words at this position of the armature the sum of the + currents in A and C will equal the − current in B and the terminals T1 and T3 will be + to T2, while with brushes, E1 is + to E2, just the opposite to the terminals. Of course with the brushes as shown, the current passing through the series field will be much less than the total amperes, as the current in A and C equals B, but only C is in contact with brush E2, therefore only the current which passes through that phase (about half the current in B) could pass through the series field, even if it were not shunted by the shunt D. In actual practice, the air gaps between the segments are less, and the brush E2 would be in contact with the segment at phase A at the same time as it was in contact with the segment connected to C. Thus with the brushes fixed in the position indicated E1 must always be + to E2. It is important that this principle of obtaining a direct current, without in any way detracting from the efficiency of the alternator, should be clearly grasped, as nearly all methods of compounding are based upon this fact.

This current, though uni-directional, will pulsate, but not seriously enough to influence the field flux, as the natural pulsations due to the few commutator segments are damped down by the self-induction of the field itself, so that, after all, these pulsations are not much greater than when the field is separately excited by direct current. It may be noted here that even when an alternator is excited by an ordinary continuous current machine, the exciting current pulsates, due to variations in the field flux set up as each armature coil passes the pole face. The effect of an armature coil when all its turns are producing a back magnetomotive force will be, for the moment it is in position "b" Fig. 15A, to decrease the field flux, which a moment later will again reach its maximum; these small variations produce an alternating E.M.F. in the field winding which

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cause fluctuations in the exciting current, as the induced E.M.F. assists or opposes the d.c. E.M.F.

The stationary shunt shown at "d" (Fig. 42) enables the attendant to adjust the amount of compounding as circumstances dictate, with as much ease as the field excitation may be varied.* There are, of course, possible methods of making a machine entirely self-exciting by winding the armature with a direct current winding in addition, and commutating it in the usual way, but there are practical difficulties which make two separate windings on one armature core objectionable. Another method is to convert current from a series transformer in the line by means of a small converter mounted on the alternator shaft. This also seems to have gone out of use owing to complication, though by suitable arrangement of the brushes it is possible by this method to compound the alternator not only for watt, but also for wattless currents—*i.e.*, to make the alternator give constant E.M.F. even with loads of varying power factor.

The work of Heyland in the direction of designing alternators which are self-exciting and compounded is among the most important advances in electrical engineering during the last few years. In his non-synchronous machines Mr. Heyland utilises the fundamental fact that an induction motor when driven by power with negative slip—*i.e.*, above synchronism, will give out power, and all his asynchronous generators are based on this principle. As induction motors have not yet been dealt with, consideration of the compensated asynchronous generator will have to be deferred till then, the fact that induction motors can be used as compounded generators, only being kept in mind, as well as the disadvantages of this type of polyphase generator viz., that it is more expensive than a

* The shunts *a*, *b*, *c*, in addition to providing an alternative path for the current, eliminate the possibility of sparking at the commutator, as the circuit is never opened, though the potential difference at the segments is in any case small, and there is little tendency to spark.

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similar synchronous machine owing to the large amount of rotor copper, and in the generating station a synchronous machine is necessary to set the periodicity.

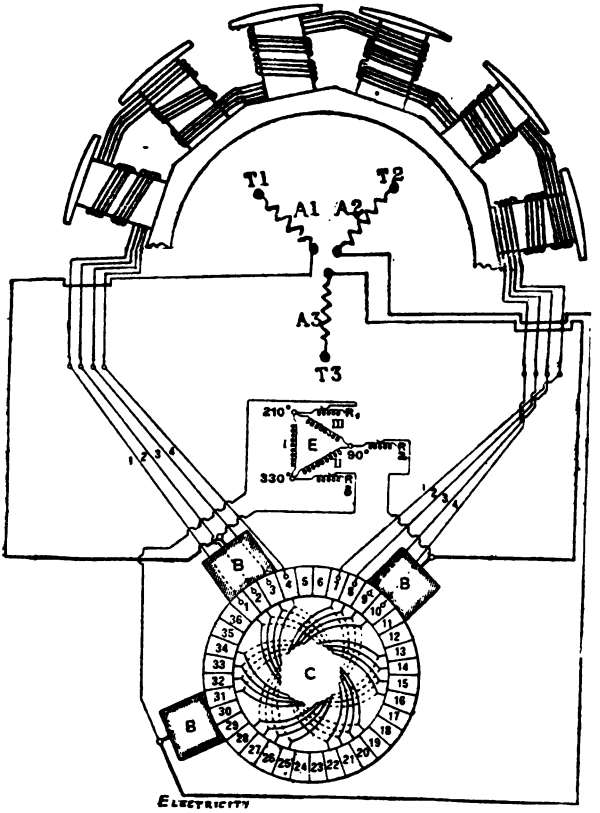

FIG. 43.

Heyland's most recent self-exciting generator is synchronous and with its connections is shown in Fig. 43, where the main armature winding is shown

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at A1, A2, and A3, and the terminals at T1, T2, T3. As in Fig. 42 the inner ends of the star are, instead of being connected together, carried to three brushes on a 36 part commutator, B1, B2, B3. Connected also to these brushes is another winding E, used only for exciting the field; this winding is delta connected, and has in series with it the resistances R1, R2, and R3, which serve to regulate the no load E.M.F. The field winding, of which six poles are shown, consists of four parallel wires through which the exciting and also the compounding currents pass. On following the connections it will be apparent that the field circuit never can be opened, and that the pulsations of the rectified current in the field magnet winding are small. Sparking at the commutator cannot take place, as the self-induction of the coil which has ceased to carry current, owing to the segment to which it is connected passing from under the brush, is cancelled by the mutual induction of its neighbour. It will be seen that the parallel wires are connected together between each pole. This reduces the difference of potential between adjacent wires and segments to the smallest possible amount, and also enables the compounding for the wattless component of the current to be effected.

The reason for these connections is shown in its simplest form in Fig. 44, where only four segments and two poles are shown. The winding consists in this case of *two* parallel wires connected in the middle at O. The brushes are adjusted so that the wattless component will flow in such a manner that it will strengthen the field, while watt currents exert no influence. If the brushes are arranged as shown, a wattless current passing through would flow *via* brush a, through the two wires 1 and 2, and back *via* segments 3 and 4, and brushes b and c, as shown by the *heavy* arrow. The watt component of the current, which would lead the wattless component by 90 degrees, would for the same polar position enter the winding by brush C, segment 4, and across the common connection O back to segment 3 and brush b, as shown

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by the dotted arrow, so that it would exert no influence on the magnetic field. By varying the brush position different degrees of compounding can be obtained, and the machines can not only meet any power factor, but can be over compounded to a considerable extent.* As the difference of potential across the brushes is between 10 and 20 volts there is no fear of sparking, whatever the nature of the load.

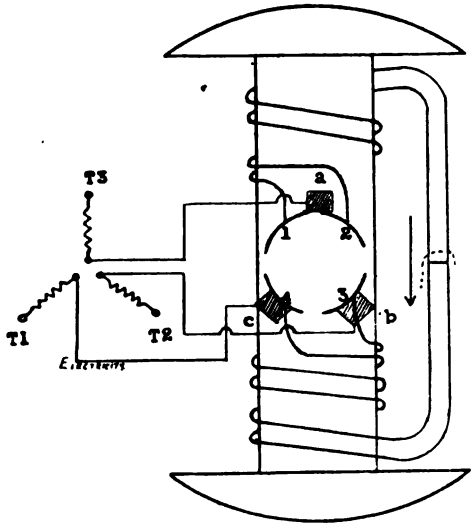

FIG. 44.

A 360 k.w. Heyland compensated alternator is shown in Fig. 45, the commutator being easily seen.

* Interesting papers on the work of Heyland and various synchronous and non-synchronous generators appear in *The Electrician*, July 3 and 10, 1903; *The Electrical Review*, July 17, 24, and 31, 1903; *The Electrical Engineer*, December 4, 1903; Proceedings of the American Institute of Electrical Engineers, May and June, 1903; Elektrotechnische Zeitschrift, October 8, 1903, and December 17th, 1903, and a discussion in the columns of *The Electrician* during September and October, 1903.

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Mr. Miles Walker has devised a method of compounding which, though not so satisfactory as the Heyland method, may be found useful where the power factor does not fall below ·85, as it gives maximum compounding at the time when it is most required, viz., at or near full-load, when the power factor is usually fairly good. Fig. 46 shows the arrangement, which consists of a small auxiliary pole protruding from the side

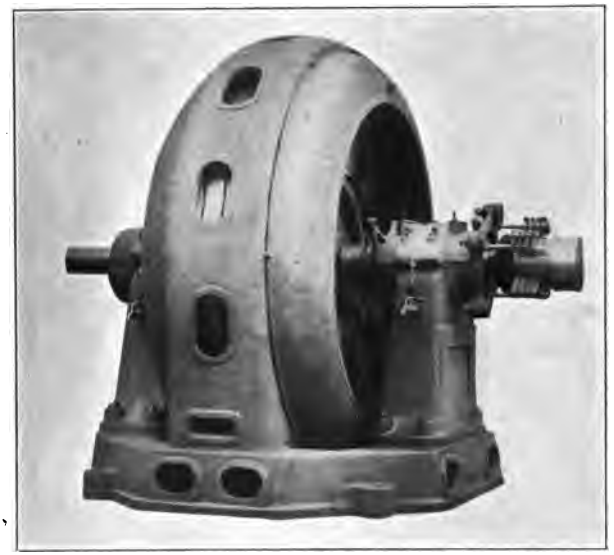

FIG. 45.—SELF-EXCITED AND COMPOUNDED THREE-PHASE ALTERNATOR OF 360 K.V.A.,'5,200 VOLTS AND 50 CYCLES.

of the main pole. The main field pole is wound in the usual way, and a small coil also carrying the field current may or may not pass round the auxiliary pole; in the illustration such a winding is shown. The field current is maintained constant and advantage is taken of the armature reaction to saturate the auxiliary

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pole. As the load increases, the effect of an armature current flowing away from the observer, will be to tend to weaken the main pole, due to the cross magnetisation weakening that part of the field magnet which is between the centre of the main and auxiliary pole, but strengthening the opposite part of the pole, *i.e.* cross magnetisation as already explained (Fig. 15A) tends to strengthen the trailing pole horn. As the auxiliary pole is unsaturated while the main pole is fully saturated, the effect of this

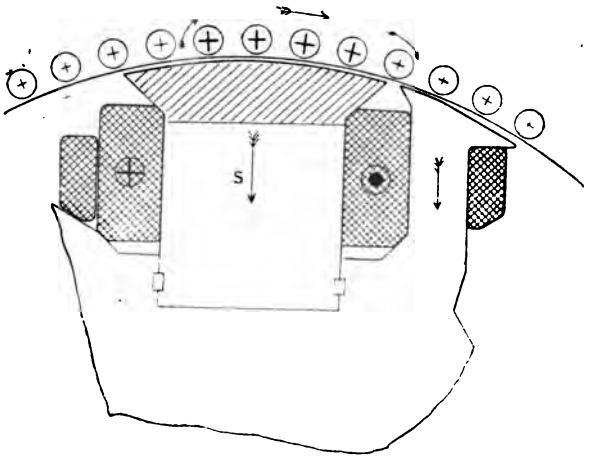

FIG. 46.

cross magnetisation is to saturate this auxiliary pole in a direction which adds its flux to that of the main pole, and so raise the field flux by the amount necessary to obtain compounding; the direction of rotation being counter clockwise in the drawing. At low power factors it will be apparent from the description given in Fig. 15A, Chap. V. that this method of compounding would not be satisfactory.

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CHAPTER XI.

Output and the Factors which Influence It.

The output of an alternator is determined chiefly by the heating limit which is imposed. In direct current practice, sparking limits have to be considered as well as heating, but only in the case of small machines is the sparking limit reached before the heating limit. In the case of alternating current machinery heating is practically the only factor which determines output. It is apparent therefore that some figure based on the linear dimensions of the rotor will give an output co-efficient or size constant of general application. It has been proposed that this "size constant" should be based the product of $d \times l$, where d is the diameter of the rotor or bore of the stator, and l the length. This is a reasonable proposition when viewed from the standpoint that heat is dissipated from the machine in proportion to its surface. It has, however, the inherent disadvantage that it is only correct for a line of machines of the same rotor diameter, because with changes in the linear dimensions the energy wasted, which fixes the temperature, does not change proportionately. It is therefore much more accurate to take the output as proportional to $d^2 \times l$, in which case results approximating to actual practice will be obtained. The cost of a machine is also more or less proportional to this quality, as obviously the cost of an alternator is much more nearly proportional to its volume than to the product of $d \times l$.*

The product $d^2 \times l$ is called the size constant and is equal to the product of watts per revolution $\times K$; where K is a constant which is determined empirically, this varies widely according to the size of the machine,

* As a matter of fact, cost is not strictly proportional to either $d \times l$ or $d^2 \times l$, but the latter is nearest.

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and is as shown in Fig. 47. The output equation, therefore, becomes—

$$\text{watts} = \frac{d^2 \times l \times r}{K} \quad .. \quad .. \quad (9)$$

where r is revs. per min., and the size constant. $d^2 \times l$ will be

$$d^2 \times l = \frac{\text{watts}}{r} \times K \quad .. \quad .. \quad (10)$$

The first of these formulas is almost identical with the better known equation,

$$d \times l \times r \times c = \text{watts}$$

where C is a co-efficient less than unity and is the reciprocal of the value K. Co-efficients of this kind must always be used with caution and should be determined, from the designer's experience, with a similar line of machines. The co-efficients given in Fig. 47 are for machines of fairly liberal dimensions, such as a temperature rise of 60 to 70 degrees Fah., after 10 hours run at full load, and a regulation of 3 to 5 per cent. on non-inductive load. By raising the temperature or lowering the inherent regulation the co-efficient may be reduced —*i.e.* a smaller and lighter machine can be produced. The interior ventilation also influences the linear dimensions, and therefore the co-efficient K. For instance, by sacrificing the efficiency, raising the temperature and carrying core ventilation to a considerable extent, it is possible to build machines of 150 k.w. having a co-efficient of only 85. Beyond 500 k.w., it is not possible to vary much from the values given in Fig. 47, and the larger the machine the more closely do modern designs coincide with the figures given.

The diameter "d" is invariably determined by the designer from considerations other than output, such as permissible angular velocity, which is influenced by the materials used in construction as already pointed out, and also by the periodicity. It is interesting to note at this point that with 50 cycle flywheel alternators the pole pitch is almost uniformly 10 inches, hence the number of poles, which are fixed by the periodicity and speed, if

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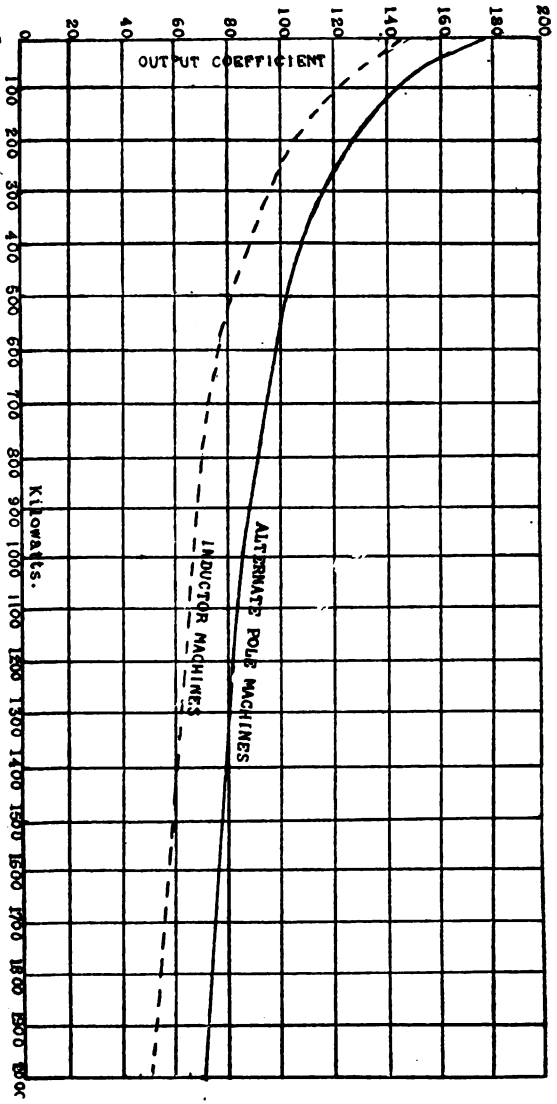

FIG. 47.

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multiplied by 10 will give the rotor circumference in inches. The figure on about a dozen of the alternators at the Paris Exhibition varied from 9·3 to 10·6 inches.

The temperature rise of an alternator is usually fixed between 60 and 80 degrees Fah., when measured on the surface of the winding by a thermometer. If the temperature is determined by measuring the increase of resistance, these figures are rather low, as the temperature at the centre of a thick magnet coil is often as much as 100 per cent. over the outside, while the inner layer, next the core, may be 40 to 50 per cent. greater after carrying full current for two hours or so. Thin coils are, however, more frequently employed, and in such cases the middle layers will have a temperature roughly 50 per cent. over the outside, and next the core the temperature will be about 15 per cent. higher, depending upon the nature of the insulation used between the windings and the core. Another important factor is the question of ventilation. The output from a given carcase with a specified temperature rise is influenced very seriously by the method by which the core is ventilated. Unfortunately no internal ventilation at all was until recently not uncommon in some alternators, although now this point is receiving careful attention at the hands of designers, due chiefly to the ever-growing keenness of competition demanding resourcefulness on the part of the designer, and the utilisation of every pound of metal in the machine to the greatest possible advantage. One way of doing this is by careful ventilation of the core. By so doing considerable saving in material can be obtained without sacrificing either efficiency or mechanical stability.

The question of internal ventilation has a buyer's as well as a manufacturer's aspect. As has been pointed out when dealing with the ageing of the core plates, the temperature at which the frequent reversals of magnetisation take place influences the growth of the iron loss. In a badly ventilated machine the internal temperature may be much higher, 120 per cent. in some cases, than the exterior, hence the core plates and the insulation of

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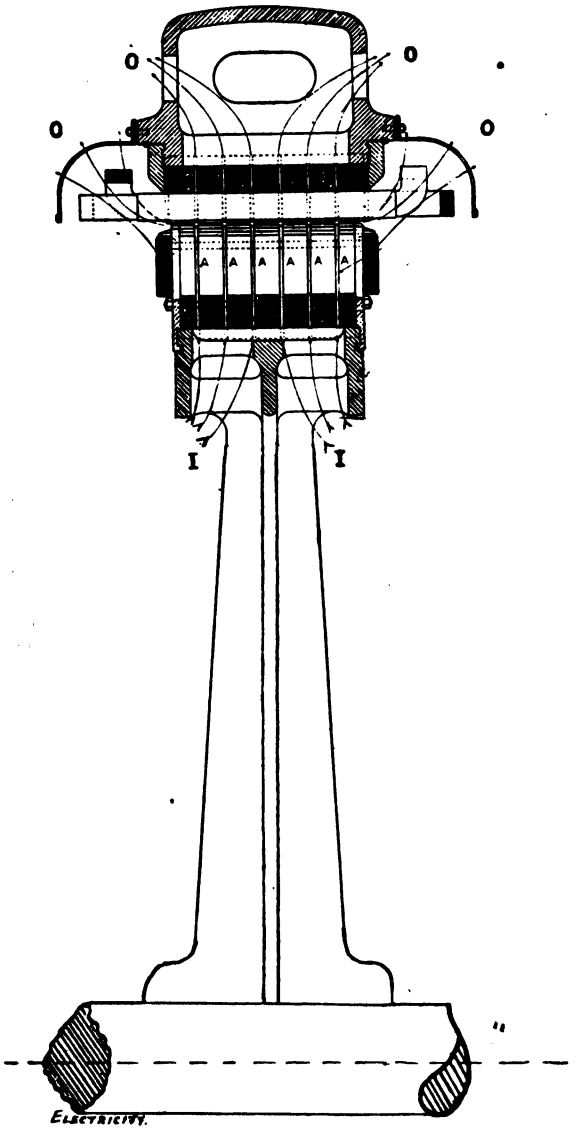

FIG. 48.

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wires in close proximity are subjected to a temperature which is likely to seriously prejudice the insulation or the windings. Fig. 48 shows the cross section of a well-designed flywheel type alternator, the arrows show the direction of the air currents which pass from the centre outwards through the ducts in the magnet and armature core, then through the openings in the cast iron armature frame. Fig. 49 shows a method of keeping the inner side of the field coil as cool as the exterior, by leaving a space between the winding and the core. Several Continental firms, and at least one American, do this;

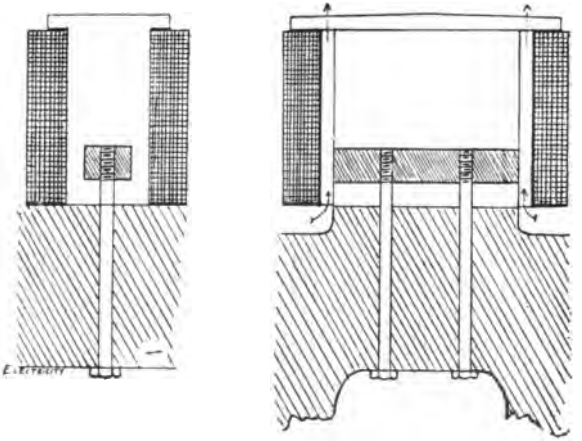

FIG. 49.

it slightly increases the mean length per turn and therefore the amount of field copper, but this is more than offset by the increase in the current density and consequent reduction in turns which result. The saving in field copper is, as a matter of fact, quite appreciable.

The energy wasted in the armature or field determines the heating, and the ease or otherwise with which this is got rid of determines the ultimate temperature. In the case of fixed armatures $\frac{3}{4}$ to $1\frac{1}{4}$ watts per square inch of exposed surface is the most that can be dissipated

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if a temperature of 70 degrees Fah. is not to be exceeded for running armatures 1 to 1½ watts per square inch. In the case of magnet coils 1½ to 2½ watts can be dissipated per square inch, and with fixed magnets, about .5 to 1. Much depends upon the ventilation, and in the case of rotating fields it is quite possible to exceed the figure given with good ventilation. The watts supplied to the field magnets for exciting purposes varies from 4 per cent. of the total watt output for 10 k.w. generators, to about 1 per cent. in 2,000 k.w. generators.

CHAPTER XII.

Determination of Characteristics of Machine.

It has already been pointed out that the amount of copper in the armature influences the regulation of the machine; how that in order to maintain the pressure regulation of the machine within practical limits the ampere wires per inch of periphery should not, in the case of slow speed alternators, be greater than a certain amount. From this it will be apparent that the terminal E.M.F. of an alternator when carrying a certain current is dependent upon, among other things, the armature reaction. It is also influenced by the magnetic leakage of the armature and field magnet.

When an alternator is short circuited, the armature current will increase until the vectorial sum of the volts lost, due to C × R, armature reaction, and self-induction in the armature, equals the volts generated by the machine unloaded. As the volts generated under the last-named condition may be said to be proportional to the exciting ampere turns multiplied by the leakage co-efficient, while the back ampere turns of the armature, when short circuited, is the maximum value of the short circuit current × the turns per pair of poles and phase × the leakage co-efficient of the armature.

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It is obvious, therefore, that the short circuit current will be approximately equal to

$$\frac{\text{Field ampere turns per pole} \times x}{\text{Armature ampere turns (max) per pole and phase} \times x_1}$$

Where x is the leakage co-efficient of the field and x_1, that of the armature, or short circuit amperes equals.

$$\frac{\text{Field ampere turns per pole}}{\text{Armature ampere turns per pole and phase}} \times Y \quad \ldots . \quad (11)$$

Where Y is the ratio of $\frac{x}{x_1}$ this ratio should take into consideration, in the case of three-phase machines, the effect of the inter-action of the phases. It can be shown that in a polyphase generator or motor, or indeed any circuit deriving its magneto-motive force from polyphase currents, the effective ampere turns are equal to the number of phases divided by 2, multiplied by the ampere turns per phase. Thus, with a three-phase machine, the back ampere turns of one armature are equal to $\frac{3}{2} = 1.5 \times$ ampere turns on one phase, and in a two-phase machine, $\frac{2}{2} = 1 \times$ ampere turns per phase. In the case of two and single phase machines, the phases being separate, their influence is less marked, only one phase being in a position to exert any influence on the field at a given time. The co-efficient Y is, therefore, greatest in the case of three phase machines. It may be taken as ·63 in the case of two phase alternators and ·35 for three phase alternate pole machines. For two phase inductor alternators the co-efficient Y is less than the figure given, being more nearly ·5. These co-efficients include a correction for the mean square values.

The co-efficients vary considerably, and should be determined experimentally for each line of machines, and then used. The figures given may, however, serve as a guide.

The short circuit current per phase is generally two to five times the normal full load amperes. Fig. 50 shows

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the short circuit curves of two alternators: "B" is that of a three phase alternator with one slot per pole and phase,

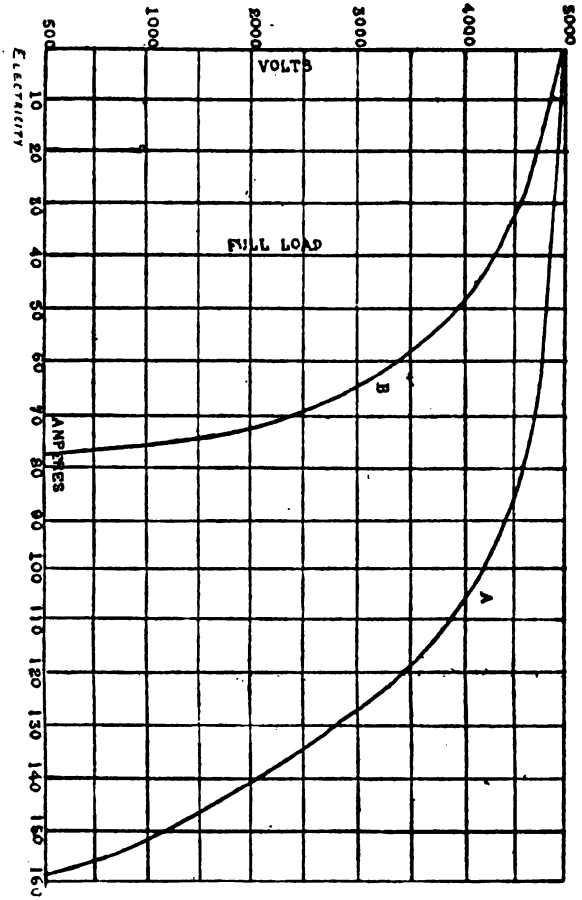

FIG. 50.

and the ampere wires per inch of periphery about 360. The short circuit amperes per phase is 1·9 times

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full load current, and the rise of pressure when the full load is switched off is 16 per cent. with fixed excitation. "A," on the other hand, shows the short circuit current of a machine with three slots per pole and phase. In this case the short circuit current is four times the full load amperes, and the rise of pressure when full load is switched off is only 4 per cent. This latter is a curve characteristic of most well-designed alternators, but it is a much more expensive machine, its linear dimensions being greater.

The drop of pressure between no-load and full-load, a most important consideration, is dependent upon four factors, which, taken together, make up what is termed the synchronous impedance of the machine. These are: (1) ohmic drop, due to $C \times R$; (2) drop due to self-induction of armature winding; (3) loss of voltage due to increase of leakage and increase of reluctance in the magnetic circuit, resulting from armature reaction; (4) actual demagnetising effect, back ampere turns, due to the wattless (lagging) component of the armature current. If the current has a leading wattless component there is a rise of E.M.F. instead of a decrease due to No. 4. It is obvious that the synchronous impedance is equal to that impedance, which if transferred to the external circuit would give the same current with the same difference of potential across its terminals. It is therefore an easy matter to determine this by short circuiting the alternator, when running at normal speed, through an ammeter, and noting the current with a certain field excitation. Now open the circuit, and note the E.M.F. shown at the terminals of the generator, the value of

$$\left\{\frac{\text{E.M.F. on open circuit}}{\text{Current on short circuit}}\right\} = \text{synchronous impedance} \quad (12)$$

The field excitation must be maintained constant, as will be apparent. The E.M.F. on open circuit is obviously equal to the E.M.F. absorbed in the machine by the four sources of pressure drop detailed above. To show the relative values of the various E.M.F.'s in the alternator the vector diagram, Fig. 51, is given.

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Draw OC as a base representing the magnitude, and direction of the armature current. Draw OE equal to the voltage of the generator *at full-load*, and displaced from OC by an angle *a*, such that the cosine will equal the power factor of the current, when the machine is on normal load (in the Fig. the power factor is ·85). Then draw ER equal to the ohmic (C × R) loss + the eddy current loss; these are obviously in phase with the current OC. With E as a centre and a radius equal to the synchronous impedance as already found, and to the same scale as all the other E.M.F.'s, draw ED, so that the vertical line RD, at right angles

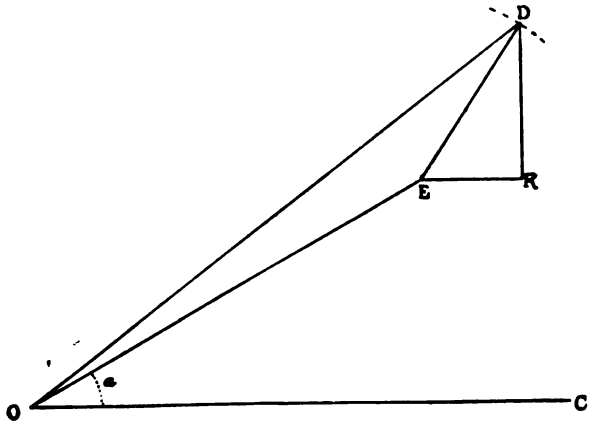

FIG 51.

to R, cuts it at D. Then OD equals the *internal E.M.F.* of the machine *at full load*, and is the E.M.F. which should be taken as a basis for calculating the flux which should be interlinked with the armature conductors. RD is the synchronous reactance. From the diagram it will be apparent that of the four sources of loss of E.M.F. in the alternator, only one—the first—acts in phase with the current, the remainder at right angles to it.

In Fig. 51 E.R. has been exaggerated for the sake of clearness; in modern alternators it has really a much

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smaller value, the principal source of drop of pressure being self-induction and armature reaction.

The chief objection to this method of measuring the synchronous impedance, especially in the case of alternators with good regulation, is that an abnormal armature current is obtained. Of course, it may be for a short time carried to two or three times normal full load amperes, but even then the field excitation may be weak; hence values of synchronous impedance may be higher than the actual amount, due to excessive armature reaction on a weak field. As, however, the short circuit curve is generally a straight line, it is easy to plot a curve

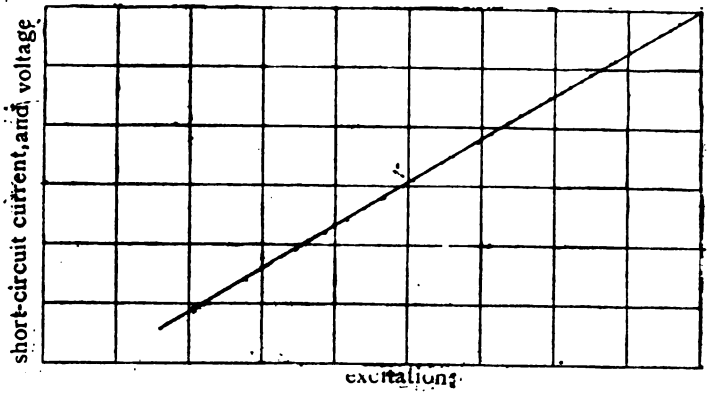

FIG. 52.

(Fig. 52) for a number of values of excitation and short circuit current and complete the line to a point corresponding to full excitation. The short circuit current so obtained will give fairly close results.

A number of other methods have been suggested, all more or less complex or based on certain assumptions in accordance with the actual conditions. Mr. Behrend in his papers* gives a good deal of information on the various methods which may be adopted.

* Transactions American Inst. of Electrical Engineers, vol. xx. (1903).

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The chief reason for introducing these other methods is that cases occur where the short circuit current curve is not a straight line. Mr. A. C. Eborall * has given an example of an alternator whose short circuit curve bends up towards the end, and in the transactions of the American Inst. E.E. just mentioned a short circuit curve turning down is shown. Under such conditions a very serious error might be introduced by assuming a straight line. This departure from a straight line appears to be influenced by the saturation of the magnetic circuit, and is not general—most commercial machines give a straight line.

CHAPTER XIII.

Waves and Wave Forms.

The wave forms shown in Figs. 3, 4, and 5 Chapter II., although symmetrical, are not by any means what are generally obtained from practical generators. While the wave form may be nearly a sine curve under full-load it may differ considerably under other conditions of load, and it is also influenced by the nature of the load, whether inductive or possessing capacity. The fundamental wave may have other waves of another periodicity superimposed upon it; these are termed higher harmonics and are analogous to overtones in sound waves. These higher harmonics are due to irregular distribution or distortion of the field flux, and are disadvantageous because they may, and often do, cause resonance—*i.e.* abnormal rises of E.M.F., due to a surging to and fro in the distributing network of E.M.F.'s which, though not synchronising with the fundamental E.M.F. of the generator, synchronise with one or other of the higher harmonics.

These higher harmonics cause resonance by increasing the capacity effect of the distributing network, as the

* Howard Lectures: Society of Arts.

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capacity current, *i.e.* the current flowing into a condenser, is proportional to the periodicity, it will be seen that these higher harmonics, by reason of their higher periodicity, cause increased capacity effects which may cause resonance.

The network itself may be considered as having a certain periodic time, *i.e.* if a wave of E.M.F. is impressed upon it, it will surge through the network and reappear at the terminals.

If that wave of E.M.F. took 1·2 seconds to traverse the network it would then synchronise with the funda-

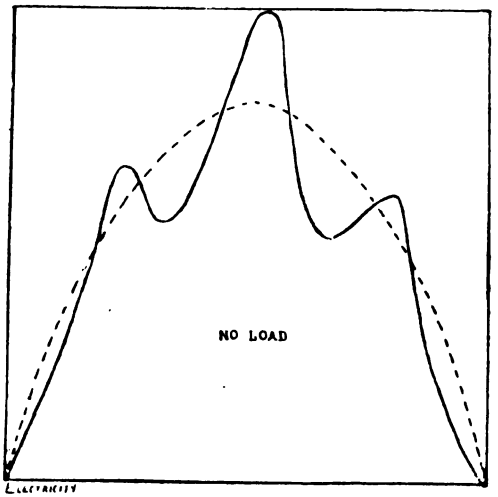

FIG. 53.

mental E.M.F. of a 50-cycle alternator, and we should have complete resonance as the periodic time of the network would be the same as that of the alternator. It rarely happens that this is so; the natural periodicity (which, by the way, varies at different times of the day, depending upon the magnitude and nature of the load), is generally greater, or the periodic time shorter, which

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is the same thing, than the fundamental wave of E.M.F. of the alternator.

This periodic time of the network may synchronise with some of the higher harmonics of the wave form, and for that reason, if for no other, it is best to get as regular a wave form as possible. Fig. 53 shows one particularly bad wave form, in which there is a distinct seventh harmonic, this is taken with the machine unloaded, and on comparing it with Fig. 54, which is the wave form of the same machine under full load, it will

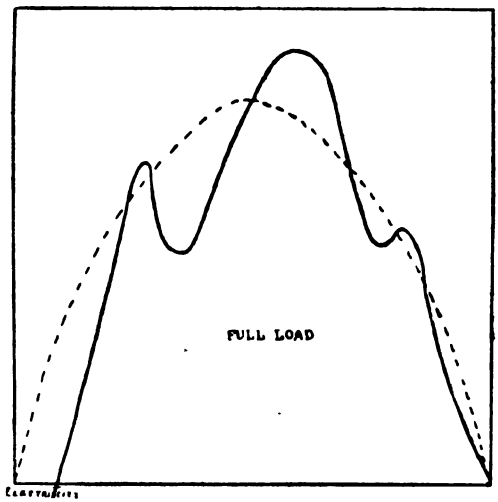

FIG. 54.

be seen that although the wave form has altered in shape, there is still the seventh harmonic, though it is not so pronounced. There is, however, a very distinct triple harmonic. The dotted lines show in each case the approximate sine curve. By special formation of the pole horns, or cutting off the edges of these, the wave form can be made nearly a sine curve as shown by Fig. 55, where there is only the merest trace of a fifth harmonic. Fig. 56 "a" and "b" show poles so shaped, "a"

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showing a graduated air gap and "b" what amounts to the same thing—unvarying gap, but graduated amount of iron. It will be seen that the wave form of an alternator is of considerable importance, not only in its rela-

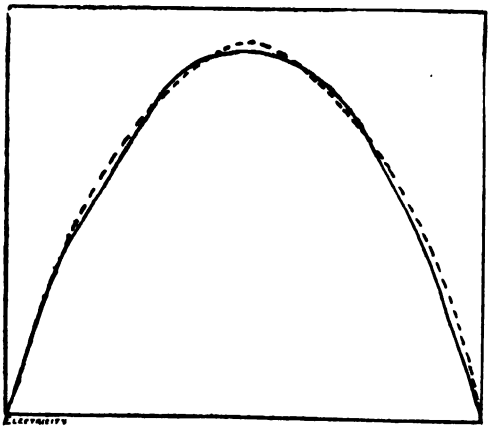

FIG. 55.

tion to the distributing system, but also to other alternators in parallel and synchronous motors, or rotatory converters. It often happens that two alternators in parallel do not have a similar wave form, and in such

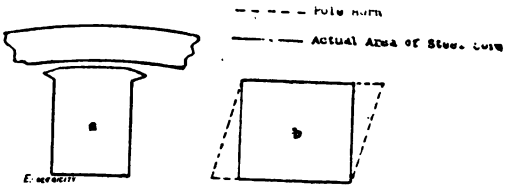

FIG. 56.

cases, even although the voltmeters show just the same E.M.F., currents will be exchanged between the machines due to the momentary difference of E.M.F. at various points of the wave. For instance it is obvious, from an

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inspection of Fig. 54, that if two machines were in parallel, one giving a wave of E.M.F. similar to the heavy line, and another a wave similar to the dotted line, there would be an E.M.F. sending a current in one direction, and a moment later the E.M.F. would be in the opposite direction, *i.e.* from one machine to the other at a frequency three, five, seven, or more times that of the fundamental wave. This would be altogether independent of another source of circulating current—viz., that due to difference in the angular velocity of the prime mover. Not only generators but motors are influenced by the shape of the wave form. Motors are often very unsatisfactory on waves different from that assumed when they were designed. Transformers also are influenced by the shape of the waves, and are more efficient on peaky than on pure sine curves. It should be explained here that Dr. Fleming has introduced the term "form factor," which is really a coefficient of peakiness of the wave, and represents the ratio.

$$\frac{\text{Root mean square value}}{\text{True mean value}} = \text{Form Factor}$$

If the wave be peaky, the root mean square value will be greater in proportion than the mean value, and if flat topped it will be less, so that the form factor is of assistance as it gives a rough estimate of the presence of higher harmonics and their probable influence on the core loss of the transformers, as the hysteresis loss depends on the flux density, which, as will be apparent, is less for a peaked wave.

A careful study of wave forms is of considerable advantage to the designer, and most electrical firms of importance have apparatus for this purpose, while practically all technical schools have the necessary apparatus for investigating the wave form.

These waves of E.M.F. can be observed in several ways; one is by fixing a contact to a point of the slip ring and observing the E.M.F. at this point; this is much the same procedure as the means adopted to ascertain the distribution of E.M.F. round the commutator of a

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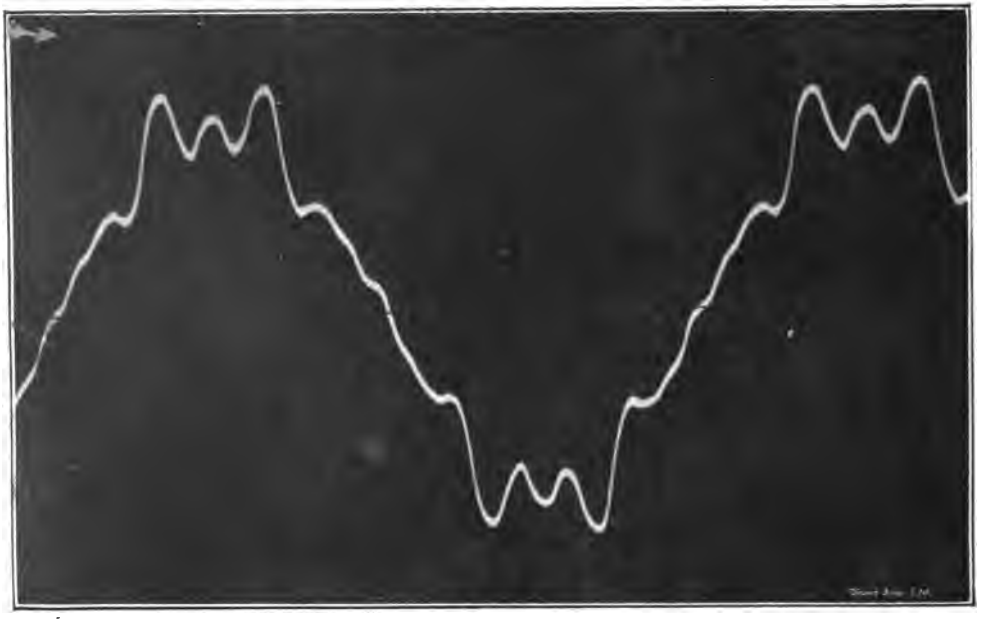

FIG. 56A.—P.D CURVE OF 5,000-VOLT THREE-PHASE GENERATOR.
The zero line is indicated by the breaks in the curves.

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direct current machine; other and now more general methods are the stroboscopic and strobographic methods described by Hospitalier to the Institution of Electrical Engineers* and the now well-known Duddell Oscillograph; the latter instrument can be supplied with a stereoscopic arrangement in which the wave form may be examined by the observer, or it may be photographed in the ordinary way; should a continuous record be desired a cinematograph film camera can be used in conjunction with the oscillograph. An oscillogram from a 5,000-volt three-phase generator is shown, Fig. 56A. The higher harmonics (ninth) are due to the teeth of the machine (it had open slots). The record was taken on a Duddell oscillograph.

Of course it must never be forgotten that the sine curve has been introduced into alternate current practice in order to simplify the calculation of alternating current phenomena; the writer believes that it was about 1881 that Joubert, in making experiments with alternate currents which varied nearly in accordance with a sine law, first introduced such harmonic variations into alternate current working. It has since then been found in practice that a sine variation is most favourable (with few exceptions), and therefore the whole theory of alternate current working has been constructed on this assumption. It would indeed be almost impossible to deal with alternate current phenomena with ease and accuracy were such a simple harmonic variation not introduced.

* *Journal of the Institution of Electrical Engineers*, vol. xxxiii., p. 35.

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CHAPTER XIV.

Parallel Running and Synchronising.

When this subject was not so well understood as it now is, parallelling troubles were pretty common in most central stations having alternate current generators. As is well known, the turning effort of a steam engine is not at all uniform, the more numerous the cranks the more uniform the turning moment, assuming, of course, that these are arranged so that the resultant turning moment is as nearly equal as possible. It is generally specified that the "co-efficient of speed variation" of the prime mover shall not be greater than 1-300 to 1-500. This co-efficient of speed variation is defined as—

$$\frac{V_2 - V_1}{V} = S \quad . \quad . \quad . \quad . \quad (12)$$

where V_2 = maximum velocity, V_1 = minimum velocity, V mean velocity, and S the co-efficient of speed variation. The lower limit of 1-500 calls for much better turning effort than can usually be obtained, except at considerable expense either in the shape of multi-crank engines or a heavy fly-wheel. The latter by storing energy and giving it out again when the engine reaches the point of minimum turning effort tends to equalise the bad turning effort of, for example, a single-crank engine. Co-efficients of 1-250 to 1-300 are found quite satisfactory, and it seems from continental experience that a co-efficient of even 1-100 is quite sufficient for satisfactory parallel working, especially if the alternator is fitted with damping coils.

The foregoing formula (12) is often stated in a somewhat different form, viz., the variation is defined in degrees of phase displacement. This is more accurate, as it takes into consideration the number of poles on the alternator. It should be pointed out that the greater the number of poles the better must be the turning effort of the engine, as the following example will show. Two alternators of different periodicity have been chosen as

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an illustration, because these two periodicities are common in practice, but alternators of the same periodicity but of different speed, the number of poles varying inversely as the speed would have given similar results, showing that for a given periodicity and with engines of equal turning effort, high speed is favourable to satisfactory parallelling

TABLE V.

	Example A.	Example B.
Periodicity	25 cycles	50 cycles.
Number of poles ..	.. 40	80
Speed of alternator.	75 revs. per min.	75 revs. per min.
Number of cranks..	2	2
Number of *impulses* per revolution..	4	4

Assuming that in each case the variation of engine speed due to the impulses of steam in the cylinder is 1·10 per cent. *above and below* the mean speed, it will be seen that for each impulse ten poles have passed a given point of the armature in the case of the 25-cycle machine, and 20 poles in the case of the 50-cycle machine (revolving field alternators being assumed), an increase of speed to the extent of 1·10 per cent. would mean that in the case of the 25-cycle machine, example A, there would be an increase of 1·100 of 1 pole, and as 1 pole equals $\frac{1}{2}$ of 1 cycle or 180 degrees (phase) there would be an advance of 1·8 degrees, that is, assuming two 25-cycle machines as above in parallel driven by two-crank engines one would lead the other by this amount, while at the same time it is just possible that the other 25-cycle alternator would at the same instant have fallen *behind* by the same amount, there would therefore be a total phase difference between the two alternators of $1{\cdot}8 \times 2 = 3{\cdot}6$ degrees. A cross-current would flow between these machines proportional to the sine of the angle, *i.e.* equal to about 6 per cent. of the short circuit current of the machine. In the case of the 50-cycle alternator example B, the 20 poles are passed per impulse, and the phase displacement is 3·6 degrees, or, assuming two alternators in parallel, one leading, another lagging behind, the mean

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by 3·6 degrees, or a total 7·2 degrees, there would be a flow of current between the two machines equal to sine 7·2 or 12 per cent. of the short circuit of the alternator. It is easy to see that such a cross-current must be exchanged between the two machines, as the wave of E.M.F. of one alternator will be ahead of the other by 3·6 degrees in the case of the 25-cycle machine, and 7·2 degrees in the case of the 50-cycle machine, as the waves from each machine will resemble the waves E and E1 (Fig. 13, chap. V.), except that, though displaced from each other, they will be of the same magnitude. We have in the foregoing dealt only with what are generally termed "forced" oscillations, which however also occur in steam turbines when the steam is admitted in puffs by the governor.* In the case of turbo alternators conditions are more favourable, as there are few poles, and it has already been shown how satisfactory high speed alternators are from this point of view.

Other kinds of disturbances are termed "free" oscillations; these are due to a sudden change of load, or a bad synchronise either of one of the main generators or a synchronous motor or converter in a sub-station. These disturbances set up a condition of unstable equilibrium which is likely to last some little time, depending upon a variety of conditions, such as the magnitude of the current exchanged between the machines, which is in turn influenced by the armature reaction and impedance of the windings (in other words, by the short-circuit current), fly-wheel effect of the apparatus, and so on.

In order to improve the parallel running of alternators and synchronous machinery generally, it is not uncommon to fit the magnet poles with what are termed damping coils. These may take the form of *amortisseurs* (or damping circuits†), metallic bridges between the poles, or closed circuits round the magnet poles. When the pole faces are solid, as is the case with a few continental designs using tunnel-wound armatures, there is no need for any of the foregoing devices as the

* This also occurs with engine-driven alternators.

† Originally due to Messrs. Hutin and Leblanc.

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eddy currents, which naturally occur in the pole faces when any movement of the magnetic field takes place, assist in steadying the machine under these conditions. The action of all these damping devices are identical, and based on the fact when two synchronous machines are in parallel, and one tends to slow down, there will be a current from the fast to the slow machine, proportional to the difference between the periodicity of the bus bars and the periodicity of the slower machine, *i.e.* the difference between the instantaneous E.M.F.'s. It is therefore obvious that the further the slow machine falls out of step the greater this current becomes. As hunting is really a condition in which the generator first gets *ahead* of its neighbour, and then falls *behind* it, it follows that this current first passes from the slow machine to the fast machine, thus pulling up the latter, and then as the fast machine becomes slower the direction of the current is reversed, owing to the machine which was, a few seconds previously, slower than its neighbour, becoming faster.

The net result of this current is just as if, first, a small lagging, then a small leading current passed through the armature (see Fig. 15a), thus causing a variation of magnetic flux across the pole face; in point of fact, there will be a distortion of the main flux, shifting first towards one pole horn, then to the other, as first one and then another machine leads. With laminated magnets or pole faces this variation in the flux exerts little influence, as few eddy currents are induced in the pole face. The *amortisseur* winding, and in a lesser degree the other devices mentioned, act just like the short-circuited winding of an induction motor, and heavy currents are induced in them, these currents produce a drag on the magnets of the fast machine; this drag ceases the moment the machines are in step, and is, in fact, proportional to the phase difference between the two machines, being greater, the further the machines are out of step, thus tending to quickly reduce the difference between the periodicity or speed of the two machines which are in parallel.

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Two poles with holes or the reception of an *amortisseur* or damper winding are shown Fig. 57 ; the copper rods which pass through these holes being riveted to a connecting bar on either side exactly as in the squirrel-cage rotor of an induction motor. Sometimes, however, a casting of copper or brass passes round the pole, and this casting, while acting as a damper, also serves as a support for the field coil. This is standard Westinghouse practice with flywheel alternators ; in point of fact, metal bobbins for the magnet coil will serve as fairly

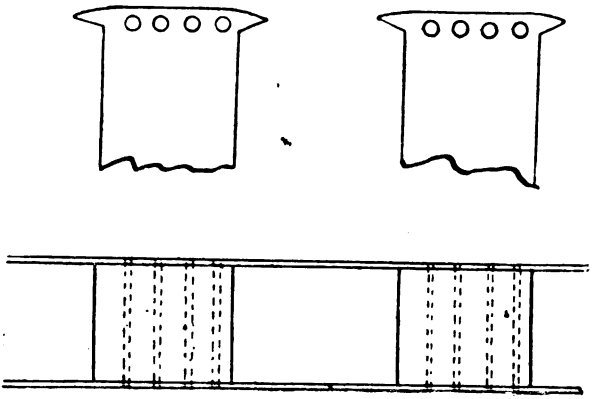

FIG. 57.

effective dampers, provided these are close to the pole horns, and are so used on rotatory converters by several European firms.

In addition to the foregoing, hunting is often caused by the governor ; too close governing is not at all necessary ; once the machines are paralleled they will tend to keep in parallel, if there are no serious disturbances elsewhere, and close governing often tends to set up hunting by causing variations of the turning effort of the high-pressure crank. The puffs of steam through the governor of steam turbines also cause trouble, but this is overcome in some turbine stations by synchronising not only the

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machines, but the governors. On the whole, it is found much easier to obtain satisfactory parallelling with turbines than with reciprocating engines; the absence of variations in the turning effort, except those due to the governors, which are of a somewhat different nature, simplifies the question.

Synchronising and Synchronisers.—Many ingenious devices have been devised for ascertaining when two synchronous machines are in step; some appeal to the eye, others to the ear. The oldest device, and one which, with a small modification, is now largely used, consists of a transformer, having two primary windings and one secondary winding with a lamp across the terminals of the secondary, as shown in Fig. 58, where A and B are two alternators. Suppose the former is running on the bus bars, and it is necessary to put B in parallel, B is run up, and excited to the bus bar voltage; it is connected to one winding of the synchronising transformer as shown. It will be seen that if the primaries are connected so that they oppose each other, each primary will induce opposing E.M.F.'s in the common secondary, and therefore no current flows in it: the lamp is therefore dark at the moment when the machines should be switched in. The lamp should be dark for three or four seconds before switching in, as it may be that the alternators are not quite in parallel, but nearly so, and the lamp would in that case glow intermittently, as the periodicity of the secondary current would be low; to switch in under these circumstances would cause no particular trouble, did the load consist of induction motors, except perhaps a disturbance of the pressure and the interchange of considerable synchronising current until the incoming machine had pulled into step. Where, however, the load consists of rotatory converters, or other synchronous machines, or there are a number of generators in parallel, all possessing considerable inertia in their moving parts, hunting may be set up over the whole system. Careful synchronising is therefore a necessity; this also draws attention to the necessity of accurate

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synchronising apparatus, and to the fact that the lamp, though simple, possesses some defects. It is desirable, for instance, to use low candle-power high voltage lamps; for with the thick filaments of high candle-power low voltage lamps, the light lags behind the current to an appreciable extent, as, naturally, the filament, when cold, takes some time to heat. This may appear of small importance, but in synchronising it is necessary to keep this point in view. Sometimes, instead of the connections shown, Fig. 58, there are two secondaries, one of which is reversed; the lamp will then glow when the machines are in synchronism, as will be seen from the connections. A hot wire voltmeter may replace the lamp in the above

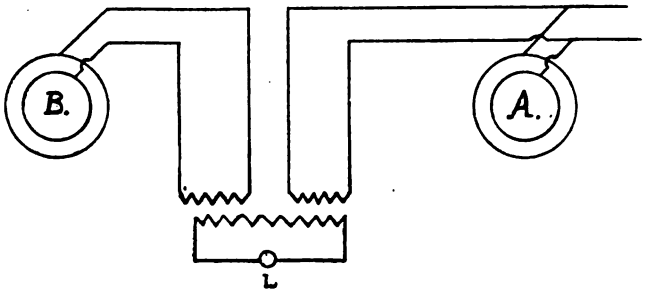

FIG. 58.

apparatus, and it improves matters, as, when such an instrument is made with light moving parts, it has a very small time lag. Sometimes, also, both are used; the lamp for the early stages, the voltmeter being switched in when the machines are nearly in step. This obviates the use of the voltmeter when the oscillations are violent, and damage to the instrument through the pointer banging against the stops is avoided.

Another optical synchroniser is that by Messrs. Siemens and Halske. It has the advantage that it indicates not only whether or not the machines are in step, but also shows whether the incoming machine is fast or slow. The apparatus is shown diagrammatically in Fig. 59,

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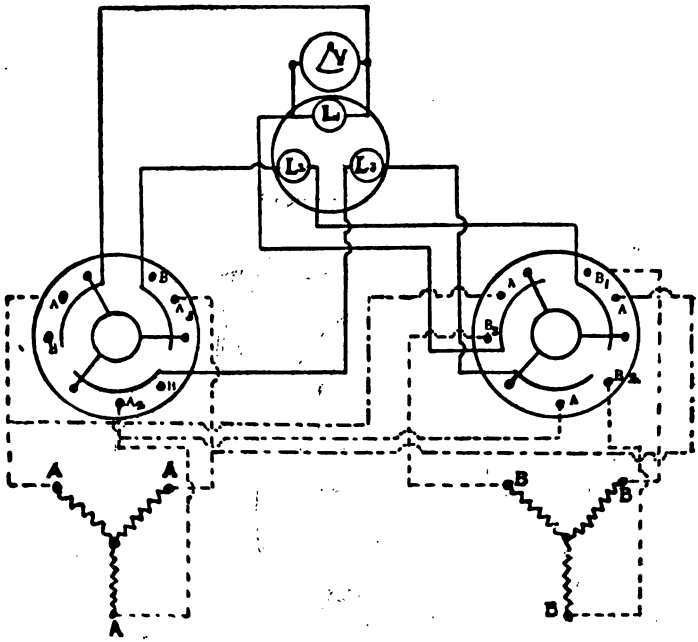

FIG. 59.

where A and B are again two alternators, the latter the incoming machine. The three quadrants on the switch are connected to the three lamps L1, L2, and L3 (the transformers, which are necessary in the case of high voltage machines, being left out). A voltmeter is also used between two lines, as shown at V. The alternator A is connected to the terminals A1, A2 and A3, and when B is to be synchronised the switch on the right hand is turned to contact B1, B2, and B3. It will now be seen that the lamps will blink just as previously described; the lamps will not, however, all be illuminated together, but first L1, then L2, then L3, if the incoming machine is fast, and the reverse if the incoming machine is too slow. The machine is switched on to the bus bars

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when L1 is dark, and the voltmeter V is zero, and when the rate of the extinctions show that the machines are at the same speed.

A more interesting instrument, and one which is being used in a good many cases, is that by Messrs. Everett, Edgcumbe and Co., which is illustrated in Fig. 60. It consists of a small induction motor, the rotor and stator of which has a two-phase winding, the stator being con-

FIG. 60.

nected to the bus bars, and the rotor to the incoming machine. If the two machines are exactly in step there will be no relative movement of the resultant magnetic field; hence no movement of the rotor, nor of the pointer seen on the face of the instrument, but if not, the rotor will move in one direction or another, depending upon whether the incoming machine runs fast or slow.

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In the Manchester Electricity Works a very simple arrangement is used to synchronise the engine cranks, and thus improve the parallel running of the machines, a practice which is common on the Continent, where horizontal single crank engines are often used. The synchronising of the cranks is carried out in Manchester by connecting a battery and telephone circuit to the valve gear, the motion of which is used to close the circuit. It is obvious that if all the connections at the valve gear are in series there will be no sound in the telephone receiver until these are all closed simultaneously, *i.e.*, when the engines are all exactly at the same point of the stroke. In some European stations a single-stroke electric bell is employed instead of the telephone receiver.

Another type of synchroniser, which, however, appeals to the ear only, was devised in the United States some years ago, and consists of an electric trumpet consisting of a small electro magnet with a laminated core, one pole of which is close to, but does not touch, a sheet steel diaphragm, not unlike the diaphragm of a telephone receiver. When the lamp shown, Fig. 58, is replaced by this trumpet it will emit a loud note, or shriek, depending upon its construction and adjustment. This will be greatest when the machines are furthest out of step and gradually die down as they come into step. When the trumpet ceases to emit any sound for a few seconds the machine is switched in. This eliminates the time lag due to the heating of the lamp, but it is not much used.

The Westinghouse Company have recently introduced an automatic synchroniser which is applicable to stations using electrically or electro-pneumatically operated switches; it is so designed that it closes automatically the moment exact synchronism is reached. It consists of a metal case mounted on the switchboard. Inside this case are two solenoids (see lower left hand side Fig. 61), the upper ends of the cores being attached to a lever swung centrally from a shaft; attached to this shaft is a suitable contact arrangement, which is, in a normal condition, open. The function of this contact device is to close the main circuit through the closing

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coil of the electric or electro-pneumatic switch on the extreme right of the diagram. Current to actuate this switch is taken from the 125 volt direct current bus bars. The converter, shown instead of an alternator in this case, is to be paralleled, and is therefore run up either from the direct current side, or by a small induction motor. The potential intrasformer "b" is connected to the three-phase bus bars, and the other primary "a" is connected to the converter side of the electrically operated switch, which is, of course, open, the other two

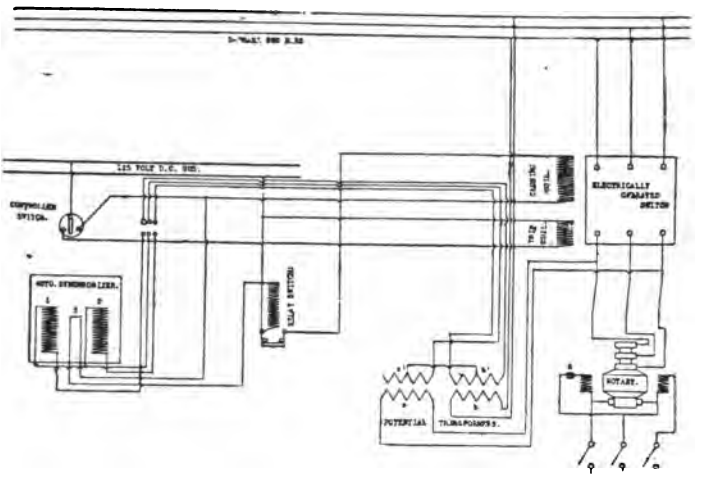

FIG. 61.—DIAGRAM OF CONNECTIONS WESTINGHOUSE AUTOMATIC SYNCHRONISER.

coils a^1 and b^1 are connected to the automatic synchroniser, which is so arranged that the left hand coil pulls down when the phase difference is 180 degrees and the right hand when the phases coincide. Connected to the contacts of the synchroniser is an ingenious device, which withdraws one of the contact brushes when one of the machines differs too much in phase. As this difference becomes less, this device acts in such a way

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as to permit contact to be made sufficiently far ahead of synchronism to allow time for the switch to operate. The relay switch shown enables the electrically operated switch to be opened, and prevents it being closed until the generator or converter has reached synchronism. The controller switch is, of course, for closing or tripping the electrically operated switch. So exact is the operation of this automatic synchroniser that scarcely any current is shown on the ammeter when the machines are thrown in parallel by the operation of the electrically operated switch. The automatic synchroniser may be adjusted to operate an electric or electro-pneumatic switch with any time lag, and as manual skill is dispensed with, absolute safety in paralleling is assured.

It is usual to synchronise only one phase of the incoming alternator, though when connecting up a new alternator for the first time it is necessary to see that all the phases are properly connected, as it often happens, particularly in the case of two-phase machines, that one or other of the phases would be in opposition to the machines already on the circuit, notwithstanding the fact that one phase might be synchronised properly. Both phases of a two-phase machine, and two of the three phases of a three-phase alternator, should be synchronised when a generator is put on the circuit for the first time.

CHAPTER XV.

Single Exciting Coil and Inductor Alternators.

It will now be desirable to deal with two types of alternator which, though not now used to any great extent, are nevertheless of practical importance, *viz.*, single exciting coil and inductor alternators. With the advent of large powers and slow speeds, they became quite unsuited to this work, though at the time of their introduction, when outputs were small and speeds high, they met with considerable favour. It must not be supposed that they are not now made. The Stanley

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Electric Co., of U.S.A., and the Oerlikon Co., Switzerland, still make inductor alternators, the former chiefly for belt driving and direct connecting to fairly high speed turbines; for the latter purpose the Oerlikon Co. also build them. Single exciting coil alternators are, however, practically obsolete, though we may possibly see a reversion to this type of machine in connection with high-speed alternators for direct connection to steam turbines. At present there seems a disposition to continue along the present lines and

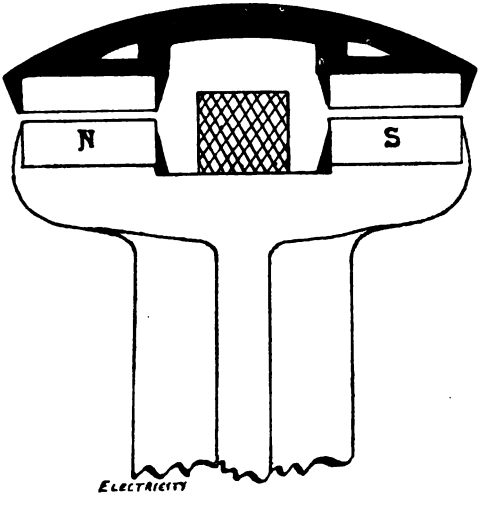

FIG. 62.

adhere to alternate pole machines for this purpose, but this may be due more to a disposition on the part of designers to continue along established lines than to any inherent defect in the type. As will be seen later, some of the most serious defects of both these types disappear as the diameter of the machine is reduced, while the modifications introduced into alternate pole designs to make them mechanically safe at high speeds,

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suggests at once the inductor or single exciting coil alternator as possible substitutes.

The principle of both these types may be gathered from Fig. 62, which shows a field magnet with a single exciting coil; the resultant poles are obviously N one side and S on the other. The other side of the magnet wheel and exciting coil are not shown. It will be seen that as such a field rotates there can be no reversal of flux in the armature, but only a variation as the polar projections pass the armature conductors; it is therefore usual to wind the armature conductors as shown in Fig. 63, A or B; the latter shows the inductor poles

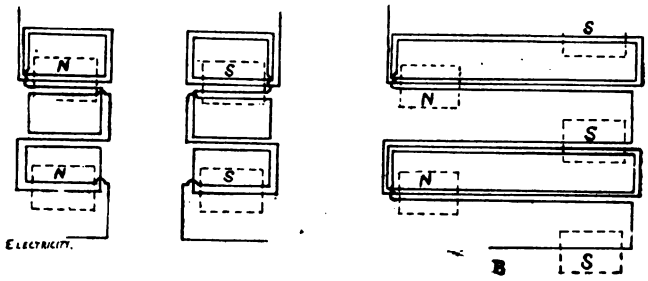

FIG. 63.

staggered. Either of these arrangements result in the change of flux necessary to produce an alternating E.M.F. It is apparent, however, that, compared with alternating flux, it requires twice as many conductors to produce the same E.M.F.; thus, for the same induction per pole, the machine must have twice as many armature conductors, and the regulation is consequently poor. This, however, can be offset by the fact that as the flux does not change in direction but only in magnitude, the induction in the armature iron may consequently be much higher for the same iron losses.

Although such alternators undoubtedly score on account of their mechanical simplicity, they possess many defects, especially when designed for slow speeds,

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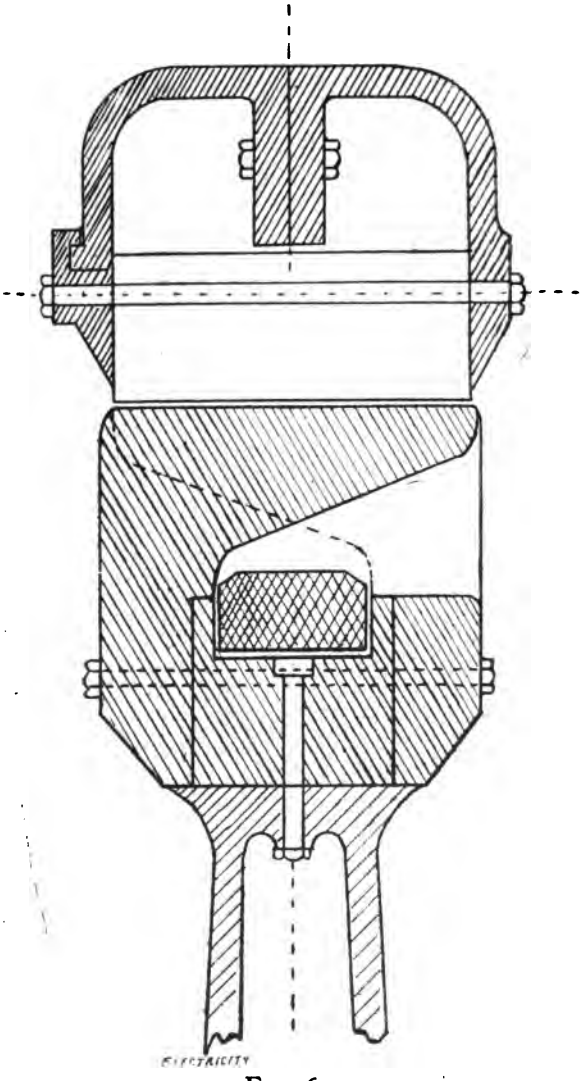

FIG. 64.

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and it is significant that their gradual disappearance was coincident with the gradual increase in output and reduction in speed which has taken place during the last few years. At one time they were made by almost every European firm of importance, though now, few make anything else but alternate pole machines. The leakage co-efficient of single exciting coil alternators is high, and as has been shown in Fig. 33, part of the leakage flux may actually be producing a counter E.M.F., so that, in addition to making the machine somewhat heavier than similar alternate pole machines, it may prove poor in regulation. Fig. 64 shows a section of a

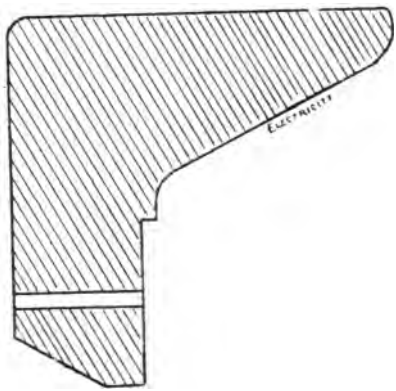

FIG. 65.

once standard Oerlikon single exciting coil alternator which was presumably designed to combine some of the advantages of the alternate pole alternator and the single exciting coil of the inductor machine. This belongs to the historic "Lauffen" type of alternator, which did good service in the infancy of the modern power transmission schemes. It had, as will be seen, an armature similar in all respects to those already described, but the magnet, although it had a single exciting coil wound on the field and moving with it, had polar

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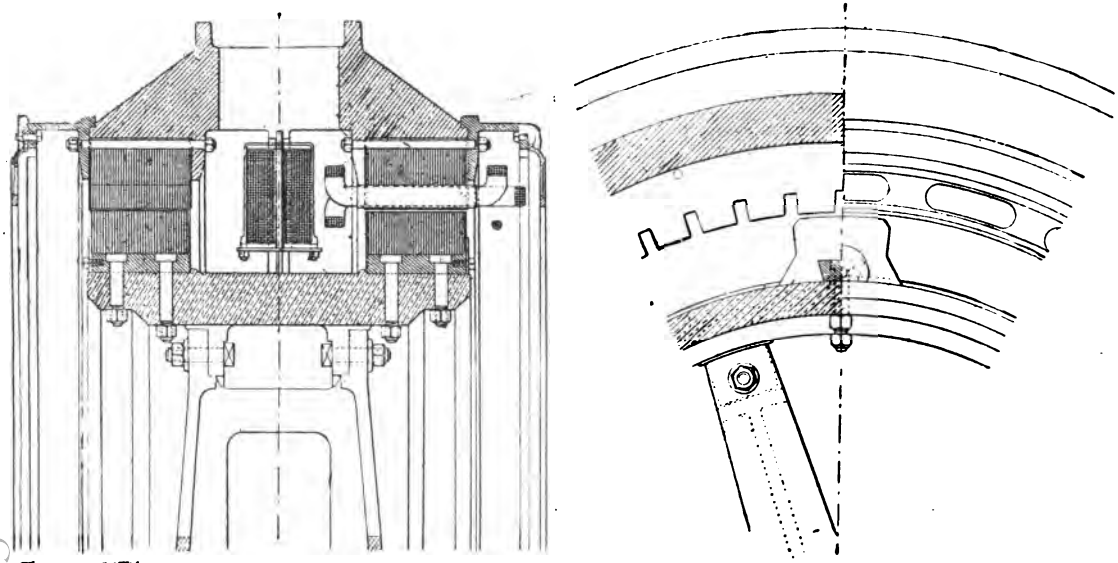

FIG. 66,—SECTION AND ELEVATION PARTLY IN SECTION. OERLIKON INDUCTOR ALTERNATOR.

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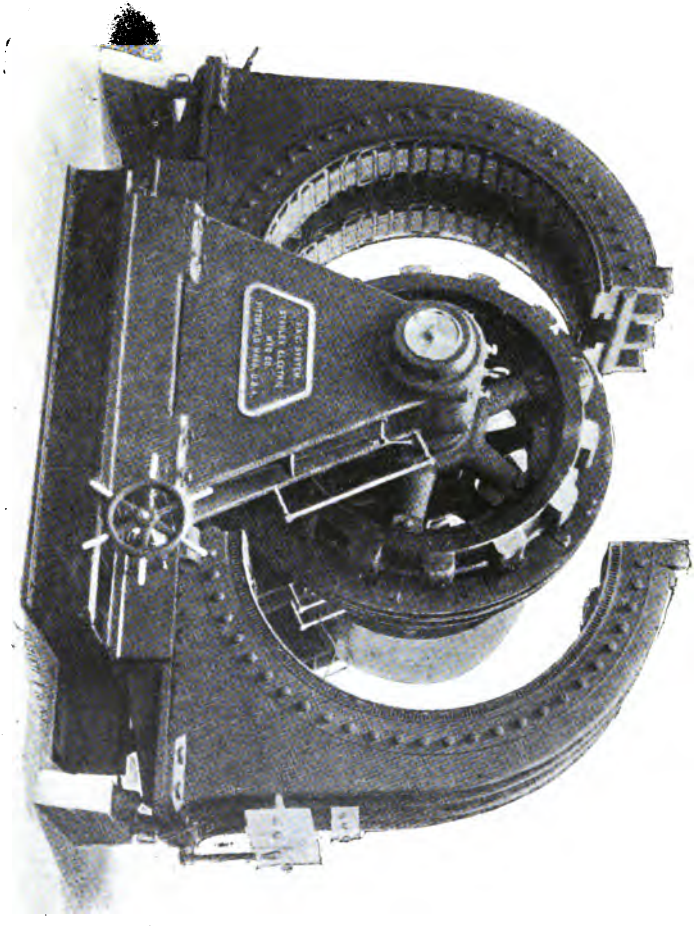

FIG. 67.

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extensions of the shape shown in Fig. 65 bolted alternately to either side of the magnet yoke thus forming a crown of poles which presented alternate N and S poles to the armature.

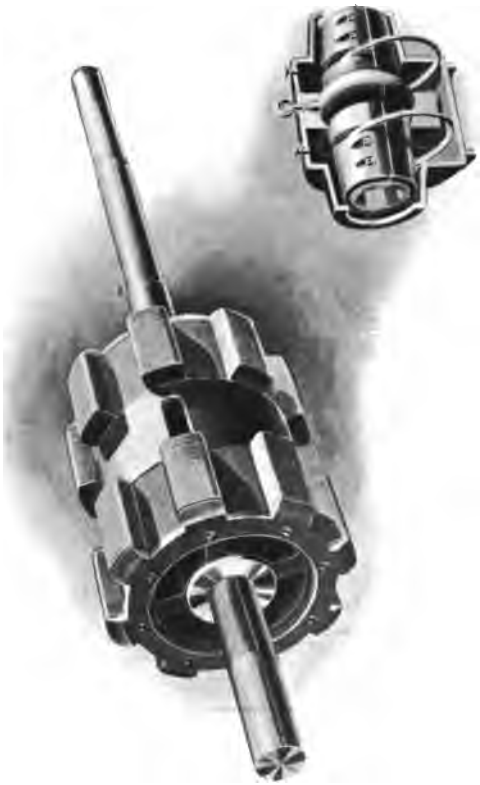

FIG. 68.—INDUCTOR OF STANLEY ALTERNATOR, BEARING ON RIGHT HAND SIDE.

The purely inductor machines of the Oerlikon Co., Stanley, Mordey, Kolben, and others, now almost forgotten, had a double armature. Mordey's single

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armature single phase machine was a notable exception. The Oerlikon alternator is shown in detail in Fig. 66 from which practically all the details of construction can be seen. Note the method of fixing the polar projections to the yoke of the inductor. The Stanley Co., in the United States, adopt a similar arrangement for their inductor alternators. A view of a Stanley two-phase machine of 600 kw. is shown in Fig. 67, the armature being racked open to expose the inductor and the single exciting coil; the latter is fixed to the bed plate. The inductor only is shown, Fig. 68. The fact that in machines of large diameter the exciting coil is not in a particularly good position for the production of magneto motive force and that on inductive loads these machines had abnormal leakage, served to put them out of competition with alternate pole types.

CHAPTER XVI.

Examples of Modern Polyphase Generators.

It would be difficult to cover all makes of alternators, even were this necessary. In recent years, however, alternator design has settled down on fairly uniform lines; competition has eliminated the freaks of other days, and it is probable that the design and construction of these machines will proceed along well-established lines; changes will take place, but these will be more of an evolutionary than of a revolutionary nature. Much attention will be given to flywheel type alternators, though, of course, the turbo-alternator will not be neglected, as the latter play an important part in contemporary engineering. Nevertheless, the days of the slow speed alternator are by no means over, as with the advent of the large gas-engine, with its high thermal efficiency, the flywheel alternator will doubtless play an important part in the future of the industry. There are so many considerations which enter into engineering progress that it is often dangerous to prophesy, but it

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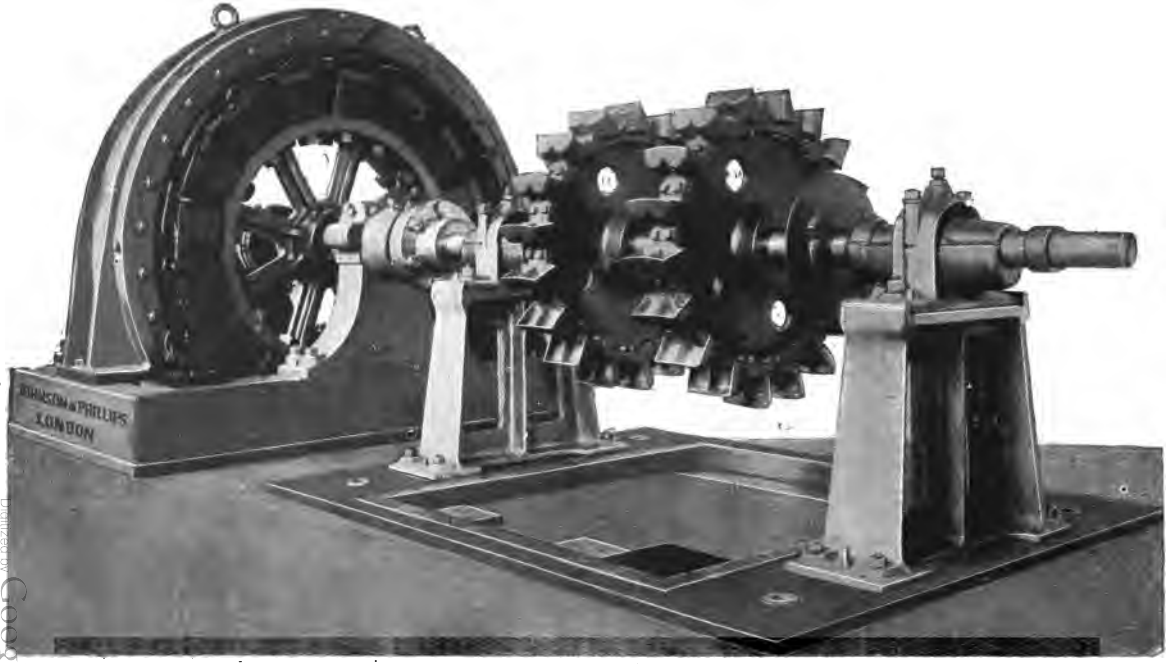

FIG. 69.—JOHNSON AND PHILLIPS' POLYPHASE GENERATOR AT REZENDE GOLD MINES.
(Casing of Pelton wheel removed.)

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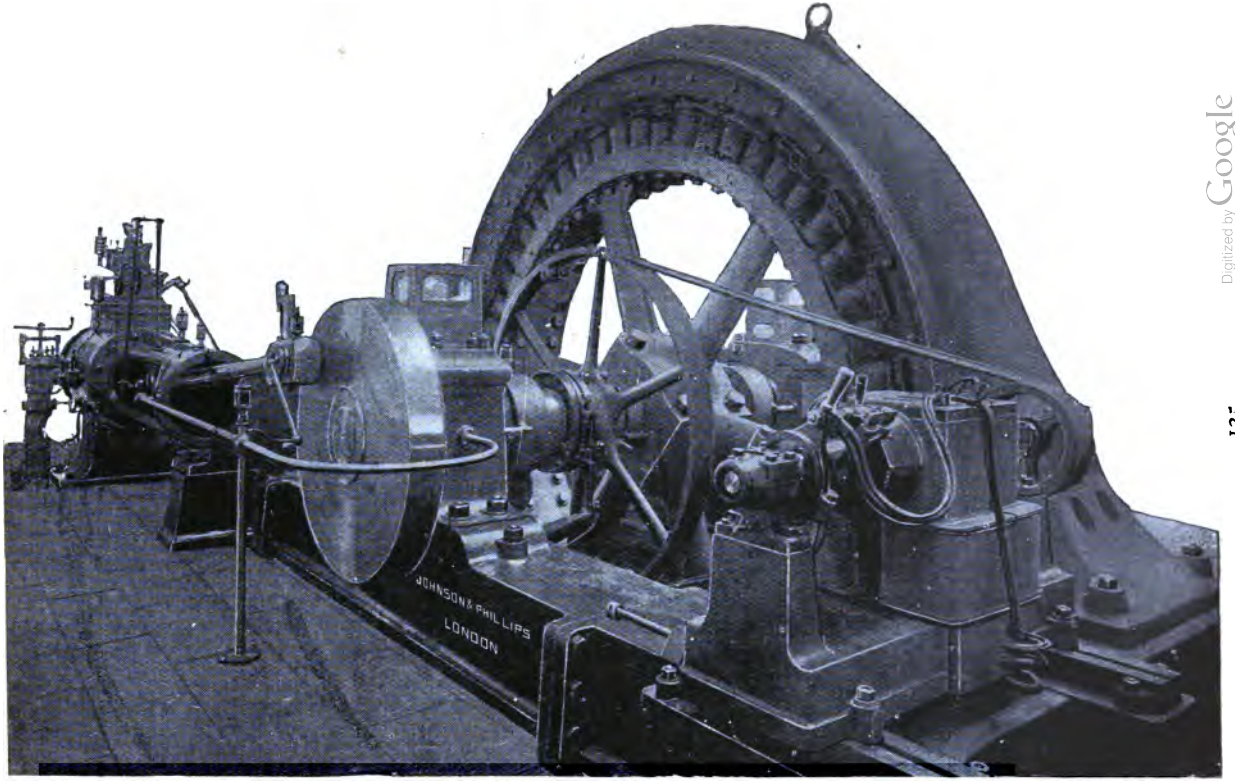

FIG. 70.—TWO-PHASE GENERATOR AT THE NORTH-EASTERN STEEL CO.'S WORKS, MIDDLESBROUGH.

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seems reasonable to suppose that these are the lines along which progress will be made. The gas turbine, while a possibility, is not within range at the moment.

We will first of all deal with the work of representative British firms, and then proceed to deal with Continental and American built generators. As has been pointed out earlier, the delay in taking up polyphase working in this country was not so much due to a lack of appreciation of its advantages, as to the fact that many of the conditions which demanded its use were absent. Firms doing much foreign work which involved power transmisson were under the necessity of taking up polyphase work earlier than those firms doing internal trade only, and among the first of these firms to take up the constuction of polyphase machinery were the Electric Construction Co. and Messrs. Johnson and Phillips. Both have a number of polyphase mining plants operating under conditions probably the least favourable to electrical apparatus and the satisfactory performance of these machines has earned for them a well deserved reputation for high-class workmanship and reliability. Fig. 69 shows one of Messrs. Johnson and Phillips' two-phase alternators coupled to a Pelton water-wheel; the casing of the latter has been removed. The field magnet poles are, as will be seen, mounted on the rim of a cast-steel flywheel, steel being necessary owing to the high angular velocity of almost 7,000 ft. per minute. The poles are laminated. and the magnet coils are held in place by the pole-horns.

The principal technical data of the machine, shown in Fig. 69, is given in Table VI. Another example of Messrs. Johnson and Phillips' design, a two-phase alternator of different design, is shown in Fig. 70. It is a slow-speed alternator of the fly-whee type designed to run at ninety revolutions per minute. The magnets are bolted to the rim of the cast-iron flywheel, similar to that shown in Fig. 35D, while the armature resembles somewhat Fig. 31.

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TABLE VI.

Type of Alternator.	High speed (rotating field) 2 phase.	Slow speed fly-wheel type (rotating field) 2 phase.
Output	165 kw.	200 kw.
Speed	400 revs. per min.	90 revs. per min.
Periodicity	53.3 cycles	40 cycles
Number of poles	16	54
Diameter of field ..	66 inches	140 inches.
Pole pitch	12.3 inches	8.15 inches.
Width of field	14 „	13 „
Winding on field	72 turns per pole 0.3″ × 0.18″ strip copper	42 turns per pole. 0.49″ × 0.245″ strip copper.
Angular velocity of field magnet	6,900 ft. per min.	3,290 ft. per min.
Number of slots in armature	160 (32 empty)	324 (108 empty).
Voltage per phase ..	2,200 volts	250 volts.
Slots per pole and phase	4	2
Turns per slot	7	1
Amperes per phase ..	37.5	400
Section of armature wire	.0195 inch	.344 inch.
Current density in armature conductors ..	1,910 amp. per sq. in.	1,160 amp. per sq. in.
Watts per revolution ..	412	2,200
Output coefficient ..	148	114

There are one or two English firms making polyphase generators of small size, all of whom seem to follow closely the practice of bolting the magnet poles to a cast-iron or steel wheel, depending upon the diameter of the rotating field. The Lancashire Dynamo and Motor Co. adopt this construction, while Messrs. Ernest Scott and Mountain, in some of their machines, cast the magnet wheel and pole in one piece, fixing a laminated pole face to the cast-steel core. This, however, only in cases where the field has comparatively small diameter, such as

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for instance, alternators for direct connection to their high-speed engines.

Messrs. Dick Kerr and Co., who have recently made many large alternators, follow American practice very closely in many details. In order to eliminate casting strains on the field magnet, the

FIG. 71.—DICK KERR ALTERNATOR, SHOWING METHOD OF FIXING SPOKES TO MAGNET WHEEL.

spider, which is of cast-iron, is cast independently, two cast-steel rings are then secured to the spokes by bolts passing through the sides, as shown, Fig. 71; the magnet cores are then bolted to these steel rings. Ventilation is obtained by casting the magnet cores in two halves, so that there is a ventilating duct right through

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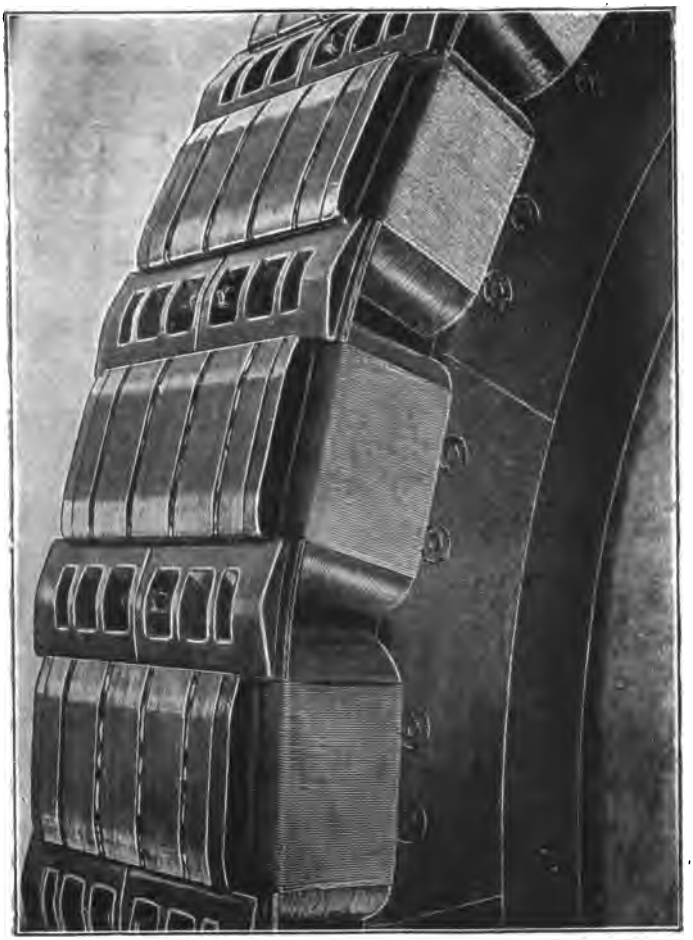

FIG. 72.—PART OF FIELD MAGNET FOR WESTINGHOUSE ALTERNATOR.

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the magnet. The pole faces are laminated and fixed to the steel core in a manner similar to that shown, Fig. 37. In their larger flywheel type alternators Messrs. Dick Kerr adopt a construction very much the same as the Allgemeine Elektricitats Gesellschaft, of Berlin—an illustration is given, Fig. 35A—the pole shoe and magnet core being laminated and in one piece ; this is dovetailed into the rim of the flywheel and keyed.

The field winding is, as usual with all firms building large machines, of copper strip, the outside layer uninsulated, save for a thin film of insulating varnish. The armature slots are somewhat similar to No. 3, Fig. 20, and after the insertion of the former wound coils the slot is closed by means of a hardwood wedge.

The British Westinghouse Co., whose field magnet construction is shown, Fig. 72, are almost the only firm whose revolving field alternators have no pole-horns. The coils are held in place by means of bridges shown in Fig. 72 ; these slide into grooves in the edge of the pole. The four ventilating ducts will be noticed, though frequently, especially with newer designs, more than four ducts are used, six or eight being common. The progress of the air through the field and armature core is seen from Fig. 48, Chapter XI.

The armature winding consists of former wound wire coils in *open* slots for small, high-voltage machines, and copper strip or bars, as the case may be, in larger machines; these bars are slipped in from the end into partially closed slots of the type shown (No. 4, Fig. 20). The end connections are bolted to the bars after the latter are in place. These end connections will be seen in Fig. 73.

Westinghouse machines have one to four slots per pole and phase. The 5,000-kilowatt generator built by this firm for the Manhattan Electric Railway, New York, is shown in section, Fig. 74. This construction differs from that usually adopted in that, instead of a cast spider or flywheel carrying the magnets, the entire wheel is constructed of steel plates, riveted and bolted as shown.

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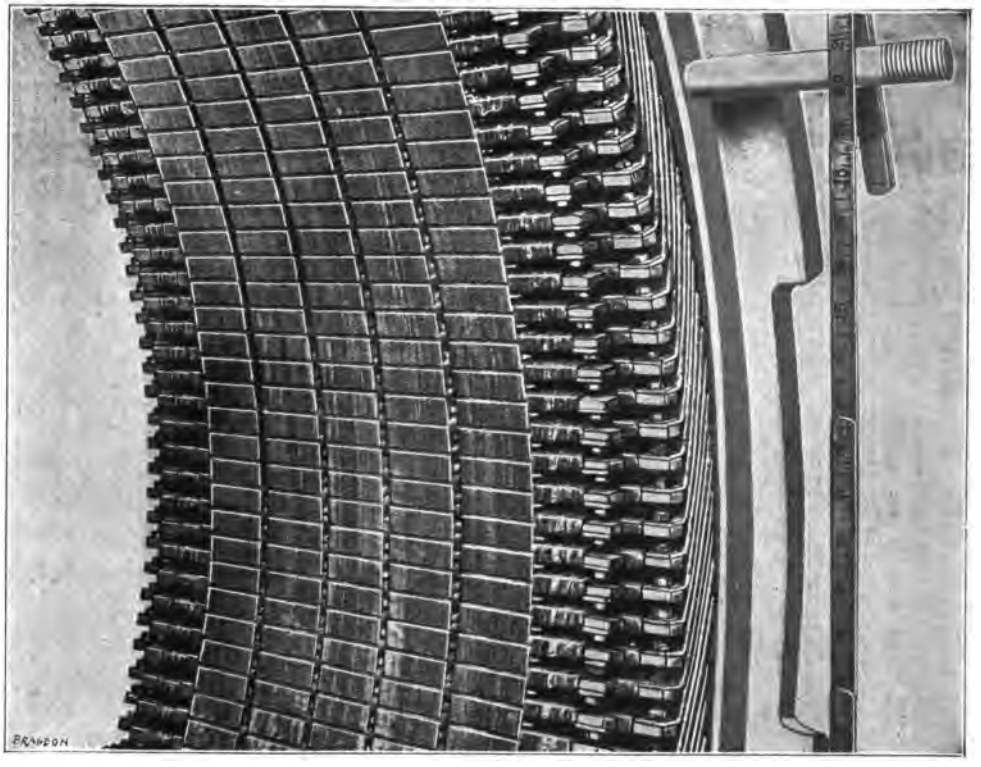

FIG. 73.—PORTION OF A STATIONARY ARMATURE FOR WESTINGHOUSE ALTERNATOR.

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At the time of writing the Electric Construction Co., of Wolverhampton, have completed similar machines for the London County Council Tramways, adopting this method of construction. Some details of these 5,000 kilowatt Manhattan Railway three-phase generators are given in Table VII.

TABLE VII.

Output	5,000 kilowatts.
Speed	75 revs. per minute.
Periodicity	25 cycles.
Number of field poles	40.
Pitch of poles	30.6 inches.
Diameter of rotating field	32 feet.
Angular velocity of field magnet	7,500 feet per minute.
Number of slots in armature	480.
Slots per pole and phase	4.
Voltage	11,000 volts.
Weight of armature	210 tons.
Weight of field magnet	148 tons.
Total weight of machine	358 tons.
Watts per revolution	67,000 watts.
Output coefficient	53.

The generators of the British Thomson Houston Co. are identical with those of the General Electric Co., of Schenectady, U.S.A. These firms almost invariably use a cast-iron spider, on to which is shrunk or bolted a steel ring; thus there is practically a fly-wheel with a cast-iron boss and arms and a steel rim. This rim serves as the magnet yoke, and to it are bolted the magnet cores, which are laminated; the method of fixing the arms and the poles will be seen from Fig. 76. The poles are, it will be noticed, rectangular. In the case of very large machines, the poles, instead of being fixed by bolts, slide into dovetails, where they are secured by keys. In all but the smallest machines it is possible to wind the machine with copper strip as shown (Fig. 75). The advantages of this have already been pointed out.

The armature of this Company's alternators has open slots, similar to No. 3, Fig. 20, in all cases; a wooden wedge is inserted in the mouth of the slot, to keep the

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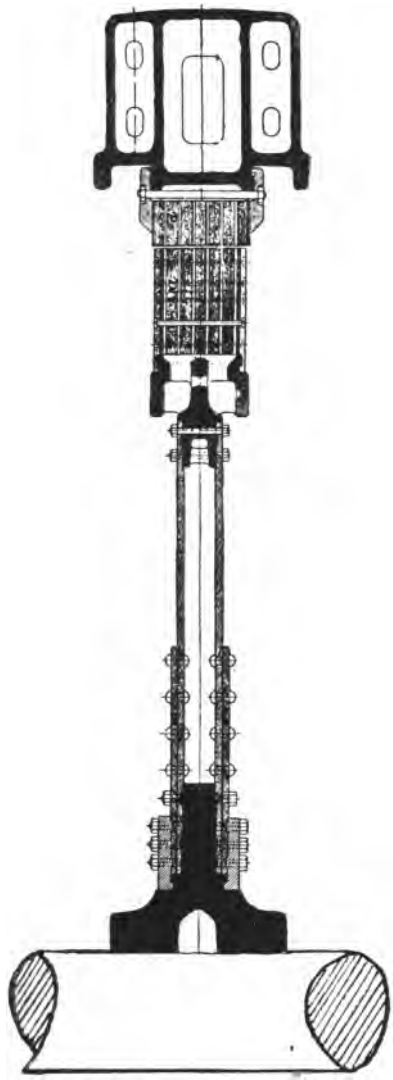

FIG. 74.

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coils in position. In the smaller machines the armature may be racked to one side to facilitate the inspection or removal of the poles, or armature coils, as shown, Fig. 76. Their machines have from one to three slots per pole and phase. Very good results are obtained from the point of view of regulation with two slots. The 700 kw. generators in the Neptune Bank Station of the Newcastle-on-Tyne Electric Lighting Co. have only one slot per pole and phase. They have a pressure rise of 7½ per cent. when the full non-inductive load is thrown off.

FIG. 75.—FIELD COIL, WITH COPPER STRIP WINDING.

Another firm whose machines embody many of the most desirable features of American practice is the Electric Construction Company, of Wolverhampton, their method of casting the boss and arms of the fly-wheel separately and bolting to it the steel rim, which carries the magnet poles, is somewhat similar to Messrs. Dick Kerr and B.T.H. practice. Fig. 77 shows a photograph of one of several 1,500 kilowatt two-phase generators built by this firm for Leeds Corporation. The voltage per phase is 2,100 volts, and the speed 200 revolutions per minute, the diameter of the field magnet is 13½ feet, which gives the abnormal angular velocity of 8,450 feet per minute, a feature which is also characteristic of the G.E.C. 1,500 kw. three-phase alternator at

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Pigeon House Station Dublin Corporation plant, which has a speed of 8.500 per minute. The periodicity is 50 cycles, and the pitch of the poles is 17 inches. This firm use open slots in all cases, and carry the armature stampings in a cast-iron frame similar to Fig. 31, Chap. VII.

FIG. 76.—120 KW. B.T.H. GENERATOR WITH DIRECT CONNECTED EXCITER, SHOWING METHOD OF SLIDING ARMATURE AND OF FIXING POLES.

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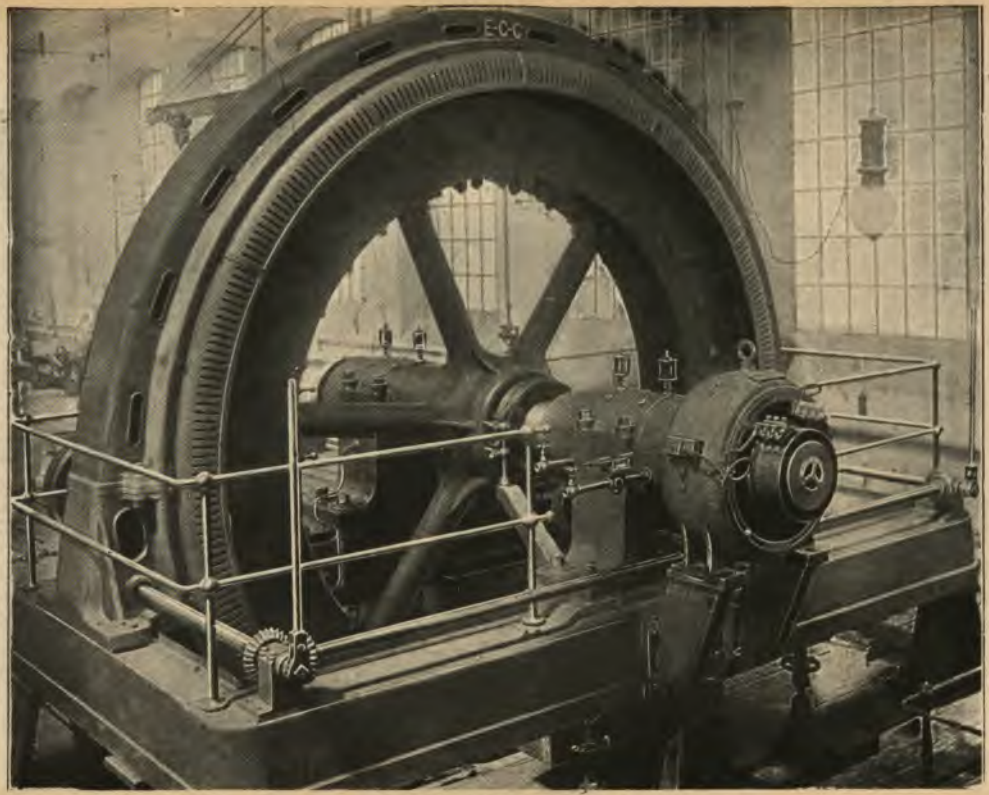

FIG. 77.—E.C.C. TWO-PHASE ALTERNATOR.

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Messrs. Bruce Peebles and Co., Ltd., make the Ganz alternators in this country; one of their machines is shown in Fig. 78, and a cross section and sectional elevation in Figs. 79 and 80. This shows the principal details of a 1,000 kilowatt polyphase alternator. The method of building the machine differs in a few points from that of the other typical machines. The armature is carried on a

FIG. 78.—1,000 KILOWATT BRUCE PEEBLES ALTERNATOR.

cast-iron frame, which is, for convenience in erection, not only divided horizontally, but vertically also; the core is carried in the shaped cast-iron clamps, which, however, differ but slightly from that of other makers. The method of fixing the magnet cores, which are laminated, resembles that adopted by Messrs. Brown Boveri, Fig. 34; the exciting winding is the orthodox copper strip. The flywheel, on which the

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magnet poles are carried, is, it will be seen, double, the bolts passing through the thinner centre part of the rim. The question of ventilation, as will be seen from the ven-

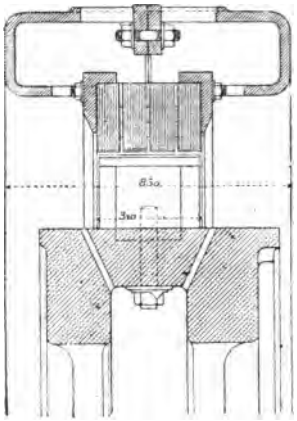

FIG. 79.—CROSS SECTION PEEBLES ALTERNATOR.

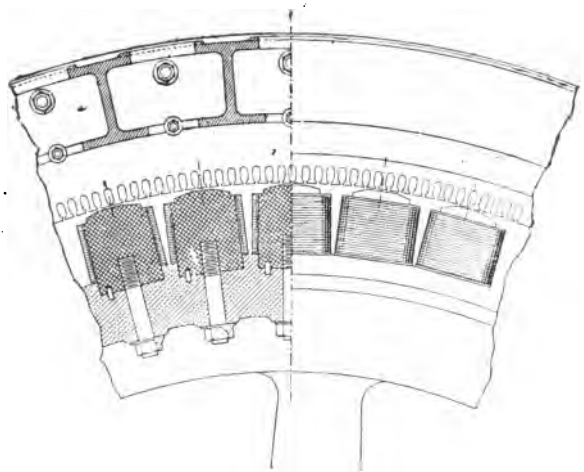

FIG. 80.

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tilating ducts, is considered. Messrs. Bruce Peebles depart from the standard practice of Messrs. Ganz and Co. in one particular—they build their machines with open slots, similar to No. 2, Fig. 20; while the practice of the Austrian firm is to use slots similar to No. 7 with a slot through the top, Fig. 80, being an elevation part in section of the Austrian firm's machines.

Messrs. Kolben and Co., Prague, whose machines have won a very favourable reputation in this country, have two excellent examples of their work in the Willesden Station of the Metropolitan Electric Supply Co. These machines (supplied by Messrs. Witting, Eborall and Co.) generate two-phase current at 10,000 volts per phase, and 60 cycles. Some particulars are given in Table VIII.

TABLE VIII.

Output	3,000 kilowatts.
Speed	75 revs. per minute.
Periodicity	60 cycles.
Number of field poles	96.
Pitch of field poles	9¾ inches.
Diameter of rotating field	25 feet.
Angular velocity of field	5,900 feet per minute.
Number of slots in armature	576.
Slots per pole and phase	3.
Voltage per phase	10,500 volts.
Amperes per phase	150.
Width of armature	29½ inches.
Width of active iron in armature	21½ inches.
Length of air-gap	0.315 inch.
Area of magnet cores	80½ square inches.
Area of pole face	157 square inches.
Turns on each magnet exciting coil	33.
Watts per revolution	40,000.
Output coefficient	66.
Efficiency full load	96 per cent.
Efficiency ¾ load	95 per cent.
Efficiency ½ load	93 per cent.

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These efficiencies are based on the assumption that the loads are non-inductive.

The flywheel is built, and the poles, which are of cast steel with laminated face, are fixed in a manner similar to that described as typical of Messrs. Brown Boveri's construction, though for a machine of this size it has been necessary to cast the armature frame in four quarters. The armature slots are open, somewhat similar to No. 3, Fig. 20, the mouth being closed with a hard wood wedge.

The 3,000-kilowatt slow speed alternator exhibited by the Helios Co. at the Paris Exhibition of 1900 and

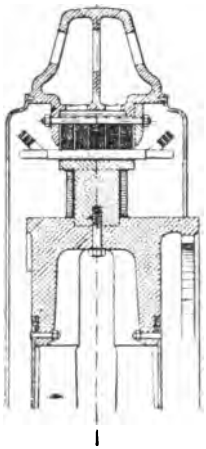

FIG. 81.

the Dusseldorf Exhibition of 1902, is illustrated in Figs. 81 and 82, the former being a cross-section and the latter an elevation, partly in section. As it is of the same output as the Willesden alternators, the only principal difference being the periodicity, the leading dimensions of these machines will form an interesting comparison. The details of the Helios alternator are given in Table IX.

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TABLE IX.

Output	3,000 kilowatts.
Speed	71½ revs. per minute.
Periodicity	50 cycles.
Number of poles	84.
Pitch of poles	12 inches
Diameter of rotating field	26¾ feet.
Angular velocity of field	6,000 feet per minute
Weight of field magnet	74 tons (without shaft)
Number of armature slots	672.
Volts between two lines	2,200.
Volts per phase	1,260.
Amperes per phase	788.
Width of armature	13⅜ inches
Length of air-gap	0.511 inches
Weight of armature	78½ tons
Area of magnet cores	53½ square inches
Area of poles faces	109 square inches
Turns on each magnet	50.
Watts per revolution	42,000.
Output coefficient	31½.

The most remarkable point about these two alternators is the difference in the output coefficient. This is not due to uneconomical design of the Kolben machine, but in a small measure to the fact that, owing to the much higher E.M.F. of the Kolben machine, a much larger amount of slot area is required for insulation; thus the copper in each slot is less than in the case of a machine of lower E.M.F. The most important consideration is, however, the difference in the periodicity, and therefore, owing to the greater number of poles, the short pole pitch. This, it will be seen, is only 9¾ inches in the case of the 60-cycle Kolben machine, while it is 12 inches in the case of the 50-cycle Helios machine. The large number of poles influences the machine in two ways; it necessitates either greater diameter to make room for the large number of poles at the normal pole pitch, or, keeping the same diameter, a wider field and shorter pole pitch with, say, oval or

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rectangular instead of round poles. The latter alternative is adopted as it tends to make the machine somewhat cheaper than an increase in diameter, the cost going up roughly about the 1.5 to 1.8 the power of the diameter. The difference in width will be seen from the tables, the diameters of the machines differ by only 5 per cent., the width of the Kolben machine is, however, 135 per cent. greater than that of the Helios machine, and its pole pitch is nearly 20 per cent. less. The former has rectangular poles, and the Helios machine round

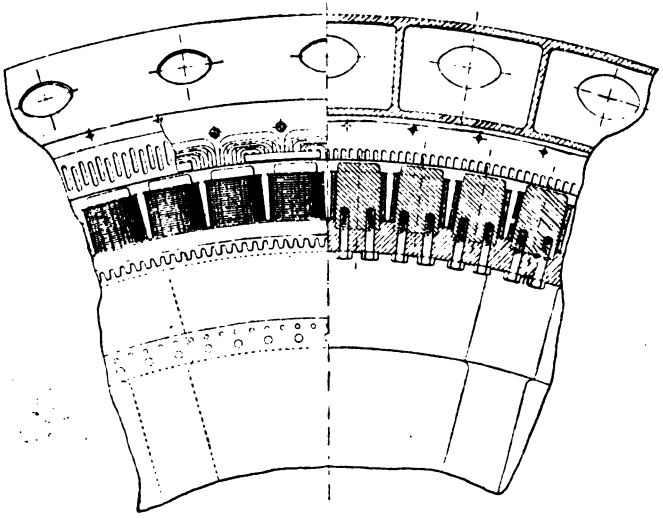

FIG. 82.

poles. Thus high periodicity alternators become difficult to design for slow speeds.

Some details of a 25-cycle slow speed alternator of 1,500 kilowatts, built by the National Electric Co., of Milwaukee, U.S.A., are given in Table X. This machine supplied power to the St. Louis Exposition, and was coupled to a 2,500 horse-power Corliss vertical, cross compound engine. The armature frame is similar to several machines already described, and presents no unusual

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features. The method of building the rim of the flywheel resembles the method sometimes adopted by Ganz and Co., the Helios Co., and several other firms. See Figs. 79 and 81. The principal dimensions and electrical details are given below:—

TABLE X.

Output	1,500 kilowatts.
Speed	83 revs. per minute.
Periodicity	25 cycles per second.
Number of field poles	36.
Pole pitch	17.6 inches.
Diameter of rotating field	16 feet.
Angular velocity of field	4,380 feet per minute.
Number of slots in armature	216.
Number of slots per pole and phase	2.
Dimensions of slots in armature	2.5 inches deep and 1.5 inches wide.
Volts per phase	3,850.
Volts between terminals	6,600.
Amperes per phase	154 amperes at power-factor—.85.
Length of air-gap	0.375 inch.
Width of armature core	16 inches
Section of armature conductors	.37 by .28 inches.
Turns of wire per slot	14.
Current density in armature conductors	1,500 amperes per sq. in.
Turns on each magnet pole	—65.
Section of field winding	1.5 0.5 ins. copper strip.
Weight of revolving field	22½ tons.
Weight of complete machine	60½ tons.
Watts per revolution	18,200.
Output coefficient	35.
Efficiency full load	95½ per cent.
Efficiency half load	94¾ per cent.
Rise of pressure between full and no load (non-inductive)	5½ per cent.
Rise of pressure between full and no load with power factor zero	22 per cent.

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The magnet cores are of cast steel bolted to the fly-wheels and the pole faces are laminated.

The machinery of the Allgemeine Elektricitats Gesellschaft, Berlin (The Electrical Co., London), has been referred to in several places, particularly their method of constructing the armatures of their large alternators. Fig. 83 is an illustration of the armature frame of the 4,250 kilo-voltamperes (3,600 kilowatts on a power factor of .85) 6,500-volt alternators at Manchester

FIG. 83.—4,000-KW. 3-PHASE GENERATOR FRAME, AS SUPPLIED TO THE MANCHESTER CORPORATION.

Corporation, Stuart Street Station. These are driven by a 6,000 horse-power four-cylinder triple expansion engine, and run at 75 revolutions per minute. These engines have been designed to give a coefficient of speed variation of 1-300 (see Formula 12), though the alternator

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poles are fitted with damping coils to still further improve the parallel running. The tie-rods, detailed in Fig. 28, are seen here. This machine has a field magnet diameter of 27 feet, and therefore an angular velocity of 6,400 feet per minute, and a pole pitch of $12\frac{3}{4}$ inches, which compares favourably with the large Kolben machines

FIG. 84.—2,000-KW. 3-PHASE ALTERNATOR. BY LAHMEYER.

at Willesden, and the Helios machine, which it more nearly resembles, being about the same diameter and having nearly the same number of field poles and speed. The weight of the field is 110 tons. The regulation is $7\frac{1}{2}$ per cent. between no load and full load, with a power factor of unity, and 18 per cent. with a power factor of .87.

Messrs. Lahmeyer, who had a most imposing exhibit

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at Dusseldorf Exhibition in 1902, exhibited, among others, the 2,000 kilo-voltampere 3-phase alternator shown in Fig. 84. It will be seen that the armature stampings are carried in a deep cast-iron framework, resembling that shown in Fig. 25, but with arms terminating in a cast-iron ring, having a diameter rather less than that of the yoke of the field magnet; indeed, this construction is a development of the construction shown in Fig. 25, with the advantage over the latter that the machining of the ends of the arms and the bolts is dispensed with, the circular boss shown in Fig. 25 being increased in diameter and the arms shortened; it increases the weight of cast-iron, but reduces the cost of the armature frame as machining is eliminated, and the latter is an expensive item with frames of large diameter. Messrs. Lahmeyer do not generally employ laminated poles or pole faces, on their machines, the poles being usually of cast-steel with removable faces also solid, or the pole and its overhanging pole face cast in one piece, which is bolted to the rim of the flywheel. This is the construction adopted for the 4,000 kilowattt 50 cycle alternators supplied by them to the Charing Cross and Strand Company. As already pointed out, this method of construction gives no trouble with partly or completely closed slots, especially if, with the former, the air-gap is sufficiently great.

The inductor type alternator described and illustrated (Fig. 66) will be illustrated by an example of an Oerlikon 3-phase inductor machine, designed on the lines shown in the drawings just mentioned. The machine has an output of 650 kilowatts, and was designed for direct coupling to a water turbine at 250 revolutions per minute—a speed which is much better suited to inductor machines than the slower speeds of horizontal or vertical engines. Details are given in Table XI., and it will be necessary to refer frequently to Fig. 66.

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TABLE XI.—PARTICULARS OF OERLIKON INDUCTOR ALTERNATOR.

Output	650 kilowatts.
Speed	250 revolutions per min.
Periodicity	50 cycles.
Number of field poles ..	24 (12 on each side of inductor).
Dimensions of poles, height	5.75 inches from surface of inductor.
,, ,, length	8.75 inches, measured in a circumferential direction.
,, ,, width	9 inches parallel to shaft.
Distance between poles ..	17 ,, ,, ,, ,,
Diameter of inductor wheel	6.19 feet without poles.
,, ,, ,, ,,	7.18 ,, over poles.
Width ,, ,, ,,	3 ,,
Angular velocity of inductor	5,600 ,, per minute.
Weight of inductor	6.8 tons.
,, ,, copper in single exciting coil	1.12 ,,
Voltage between terminals	7,500 volts.
,, per phase	4,330 ,,
Amperes ,, ...	50 amperes.
Number of slots in armature	72 on each side.
Slots per pole and phase ..	2 ,, ,,
Weight of armature and cast-iron frame	13.8 tons.
Weight of armature copper ..	1,200 lbs.
Watts per revolution ..	2,600
Output coefficient	52
Rise of voltage when full load is switched off	3½ per cent. on full load having power factor .8.
Exciter amperes no load ..	55 amperes.
,, ,, full load (at .8 power factor)	88 ,,
Efficiency on full load .8 power factor	92 per cent.

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The foregoing is an excellent example of an inductor machine, and shows that for high speeds they can be built economically, so far as active material goes, and to give good results from the point of view of pressure regulation and efficiency. The chief disadvantage is that the percentage of dead, inactive material increases the linear dimensions, particularly the width, to an undue

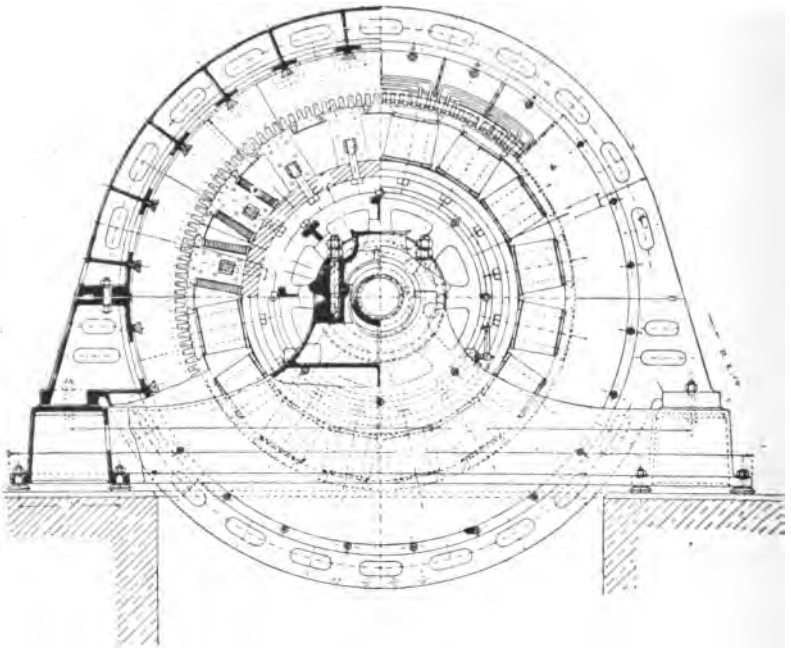

FIG. 85.—OERLIKON 3-PHASE ALTERNATOR.

extent when compared with alternate pole types; this becomes increasingly apparent as the speed is reduced.

As a contrast to this inductor alternator, the following particulars of an alternate pole machine, also by the Oerlikon Co., and of exactly the same rated output, is given. The machine as built was for a speed of

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375 revs. and proportionately greater output, but the output was in other respects comparable, and the watts, per revolution, naturally identical. The elevation, partly in section (Fig. 85) will give full details of the construction, and Table XIA. gives a few details :—

TABLE XIA.—PARTICULARS OF OERLIKON ALTERNATE POLE ALTERNATOR.

Output	930	kilowatts.
Speed	375	revolutions per min.
Periodicity	50	cycles.
Number of field poles ..	16	
Diameter of field magnet	6.4	feet.
Width of field magnet ..	$16\frac{7}{8}$	inches.
Pole pitch	15	inches.
Watts per revolution ..	2,500	
Output çoefficient	40	

Regulation is the same as for the inductor alternator but owing to the greater output, the efficiency is rather better.

An alternator by The Société Alsacienne de Constructions Mécaniques, which was exhibited at St. Louis Exposition, is shown in elevation (Fig. 86) and in section (Fig. 87). This machine gave 850 kilo volt amperes, and ran at 94 revolutions per minute ; it has 64 poles, and consequently gives a periodicity of 50 cycles per second, the voltage being 2,300. The constructional details will be clear from the drawings given.

Figs. 88 and 89 show a popular type of generator on the Continent, where the alternator has to be coupled to a comparatively slow speed turbine, such, for instance, as the slow and medium head falls in Northern Italy, Switzerland, and some parts of France. They are also better known through their employment at Niagara Falls, though in that case many of the generators have the rotating field fixed outside the armature. Of course, the developments on the Canadian side of the falls have been on more orthodox lines, and so far as the author is aware this is almost the only installation of any size in the United States using such generators, though they are fairly common in Europe.

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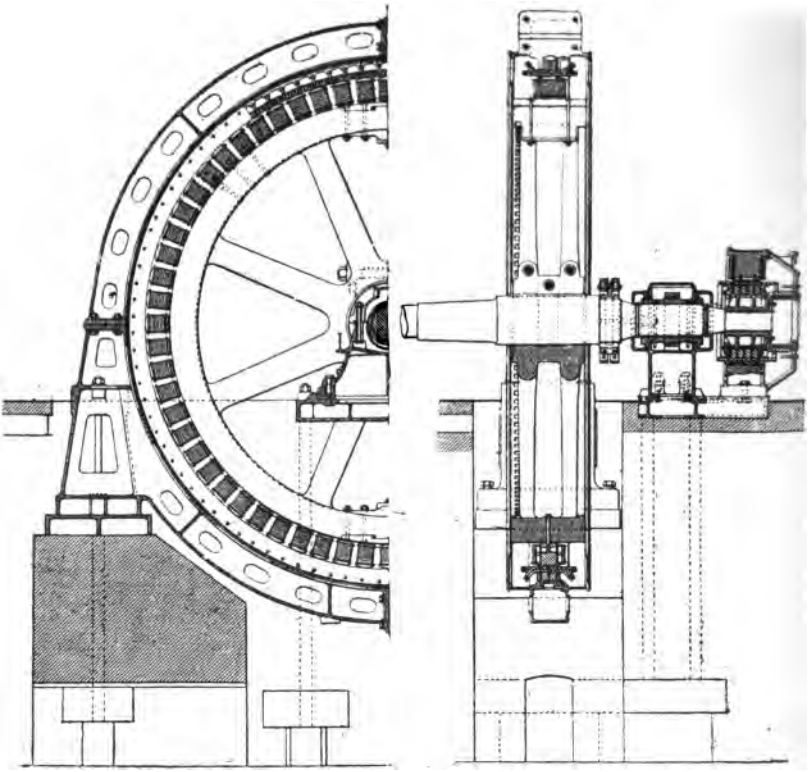
The illustrations show a 1,000 kilowatt Brown Boveri umbrella type alternator; the diameter of the rotating field magnet is 13.1 feet, it has 50 poles, the speed 120



FIGS. 86 AND 87.—850 KW. ALTERNATOR BY THE SOCIETE ALSACIENNE DE CONSTRUCTIONS MECANIQUES.

revolutions per minute, and the periodicity is therefore 50 cycles per second.

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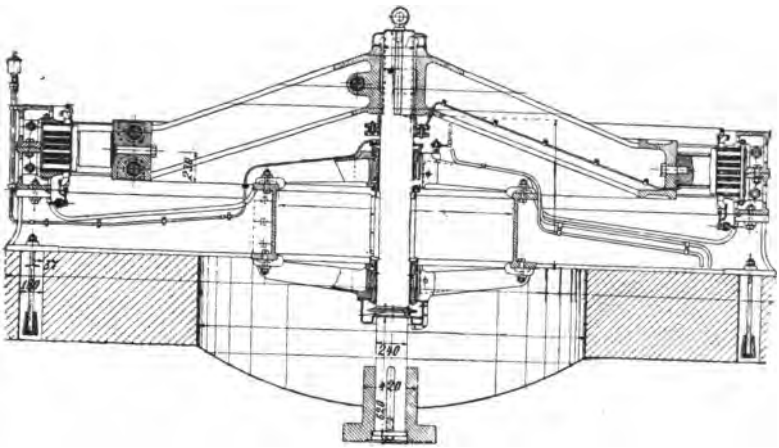

FIG. 88.—SECTION THROUGH 1,000 K.V.A. BROWN BOVERI UMBRELLA TYPE ALTERNATOR.

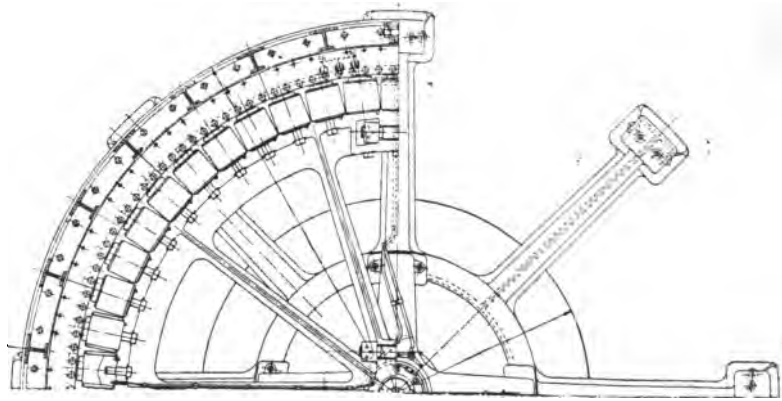

FIG. 89.—PLAN OF BROWN BOVERI 1,000 K.V.A. UMBRELLA TYPE ALTERNATOR.

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CHAPTER XVII.

TURBO ALTERNATORS.

The rapid progress made by the steam turbine has created a demand for special types of alternator; machines, though not differing seriously, except in isolated instances, from standard alternate pole constructions, have had so many modifications introduced into details that they may be said to form a distinct class by themselves. These modifications have been rendered necessary by the high speed of rotation—in some cases 3,000 revolutions per minute. At these high speeds, which are equal to angular velocities of nearly 15,000 feet per minute, the resources of the designer are taxed to produce a structure which, it must not be forgotten, has magnetic strains in addition to the mechanical stresses due to speed. Moreover, the case is complicated by the fact that in these small high-speed machines, the limit has been passed where the machines can be cooled without difficulty. Owing to the high speed, the iron losses become of considerable magnitude. The $C^2 \times R$ losses are also great owing to the large output; but owing to the speed, the dimensions, and, therefore, the ability to radiate heat, has been reduced very considerably, hence the most careful ventilation by means of fan blades—and in some cases even water cooling—has been resorted to in the armature. Low periodicities of 25 cycles are particularly unfavourable to steam turbines, as they can only be run at speeds of 1,500 revolutions per minute (two pole) or 750 revolutions (four pole). The latter speed is rather low for modern turbines (except Curtis), and large steam turbines are generally built for speeds of 1,500 and 1,000 revolutions.

The output coefficient, especially in the case of 3,000, 1,500, and 1,000 revolutions turbo-alternators, will be found considerably greater than that given for slow speed machines, about 20 to 50 per cent. over the values given in Fig. 47 being representative of

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modern practice, though a great deal depends upon the ventilation.

As in the case of slower speed machines, a rotating field is preferred by most firms owing to the comparative ease of insulating the fixed windings; moreover, as these windings have considerable mechanical stresses in addition to electrical stresses, if the armature rotates, the operating conditions, become particularly unfavourable, hence, with trifling exceptions, practically all turbo-alternators have revolving magnets. That the forces acting on these magnet poles are great is apparent when we consider the case of a single pole weighing, together with its exciting coil, say 900 lbs.

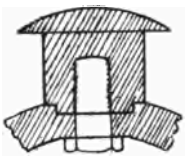

FIG. 90.

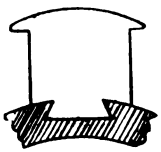

FIG. 91.

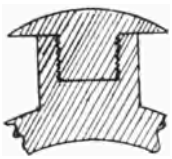

FIG. 92.

The centrifugal force due to that pole at 1,500 revolutions per minute is

Wt × r × revs.^{2} × .00034 = centrifugal force in lbs.

where Wt = weight of pole and winding, and r = mean radius, the result, substituting the values which we have, is a figure sufficiently large to warrant the careful choice of materials and excellent design, if a reliable machine is to be constructed. In turbo alternators, we have, therefore, great attention paid to the method of securing the poles or pole faces to the magnet yoke or core.

Figs. 90, 91, and 92 show methods of fixing the magnets or the pole faces. Some of these resemble the methods already considered for slow speed alternators; but the bolts and nuts are more massive, so are the dove-tails where these are adopted. Fig. 93 shows a four-pole magnet wheel by a German firm. The pole faces are secured by very heavy bolts. With a winding of this

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kind, even although it consists of copper strip, special precautions must be taken to secure it, and it will be seen that light angles of the shape shown in the figure between the two wound poles give the necessary security. The Union Electrical Co., of Berlin, have, I believe, some German patents on this method of supporting the winding.

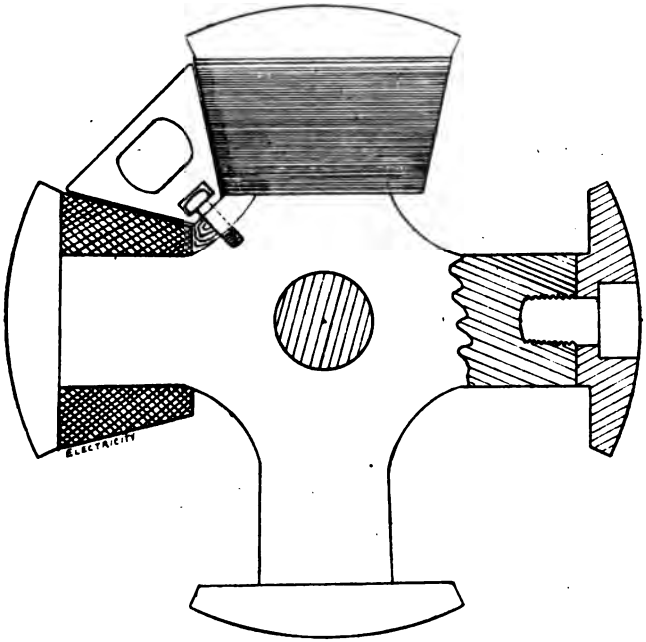

FIG. 93.

The pole pieces are solid steel castings, so also is the magnet wheel. The method of fastening shown is, therefore, very satisfactory, particularly as it permits of the field coils being slipped on, and the pole pieces subsequently fixed. As the armature is tunnel wound, eddy currents in the solid pole pieces are not to be feared. In order to reduce windage and permit the

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air currents to pass only from the hub outwards, both ends are frequently covered by saucer-shaped discs, which make the field resemble a smooth cylinder, except that close to the shaft the discs are pierced with ventilating holes.

Messrs. Parsons have made a number of very satisfactory two-pole machines for 50 cycles at 3,000 revolutions with rotating armature. These machines, which vary from 75 to 300 kilowatts, have output co-efficients varying from 165 to 115.

As the number of poles in these turbo alternators is strictly limited, there being generally four or six, the ampere wires per pole, and therefore armature reaction, is much greater than with slow speed alternators of similar output. There is, consequently, greater difficulty in obtaining good pressure regulation. Indeed it is difficult to keep this within practical limits, and modifications, apparently puzzling at first sight, are introduced to obtain the desired result.

In slow speed alternators the length of the air-gap is determined almost exclusively by mechanical considerations, but in the case of turbo alternators, owing to the armature winding being concentrated in two, four, or six poles, the armature back ampere turns per pole are more numerous, hence its demagnetising effect is much greater than in the case of machines with a larger number of poles. Were the air-gap short, only sufficient for mechanical considerations, the ampere turns necessary on each pole of the field magnet would be very small, as the reluctance of the magnetic circuit, even at a very high density, would be comparatively small, while, as has already been shown, the armature reaction would be very great. Thus, with very little armature current the reaction would be sufficiently great to, in all probability, entirely neutralise the field ampere turns. By lengthening the air-gap we increase the magnetic reluctance of the circuit, and thus place greater resistance in the path of the armature reaction; this longer air-gap also involves a greater resistance in the path of the field flux and necessitates

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the use of a larger number of ampere turns on the field. The effect of the long air-gap is therefore cumulative. It reduces the effect of the armature reaction, and renders necessary a very substantial increase in the ampere turns on the field, and, as has been shown, when dealing with armature reaction it is the relation between the field and armature ampere turns which, to a large extent, determines the regulation of the machine. Air-gaps of 2 to 2½ inches are therefore not uncommon in turbo alternators.

One favourable point is the pole pitch, which is much greater than with slower speed alternators, and, there

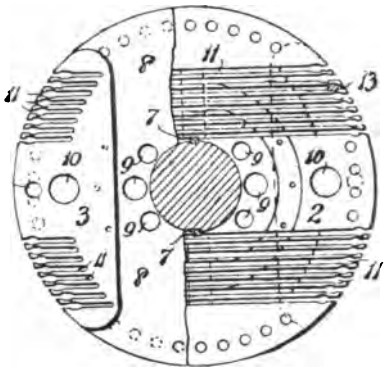

FIG. 94.—SECTION WESTINGHOUSE TURBO ALTERNATOR, CLYDE VALLEY POWER COMPANY.

fore, the leakage is reduced. As has been shown, a pole pitch of about 10 inches is fairly uniform in the case of slow speed alternators, but with turbo alternators, from 14 inches at 300 kilowatts to 50 inches at 2,000 kilowatts will be found representative of current practice. Of course, there is no uniformity, but these figures are given as some indication of the pole pitch found in such alternators.

So far, turbo alternators having definite pole windings only have been described, but the Oerlikon Co.

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have developed a ring winding, which resembles the distributed winding of a direct current armature. The Westinghouse Co. make a machine having a polar winding distributed in several slots. This is shown in Fig. 94 for two poles and Fig. 95 for four poles. The ventilating ducts are easily seen. Messrs. C. A. Parsons and Co. use another winding, which is in many respects similar except that instead of slots, the winding is

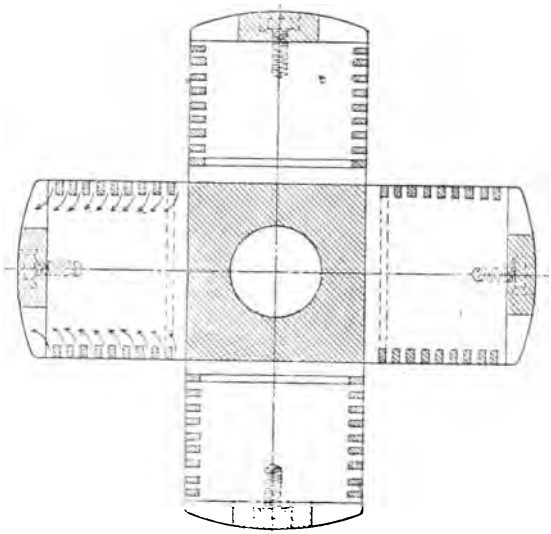

FIG. 95.—SECTION OF WESTINGHOUSE FOUR-POLE FIELD MAGNET, LOTS ROAD POWER STATION, DISTRICT RAILWAY.

wound through holes. This gives excellent mechanical support to the winding, Fig. 96.

The British Thomson Houston Co. have a definite polar winding, but the coils are secured by bundles of sheet steel, as shown in Fig. 97, then these are fixed by keys which pass through the magnet core as shown in the section.

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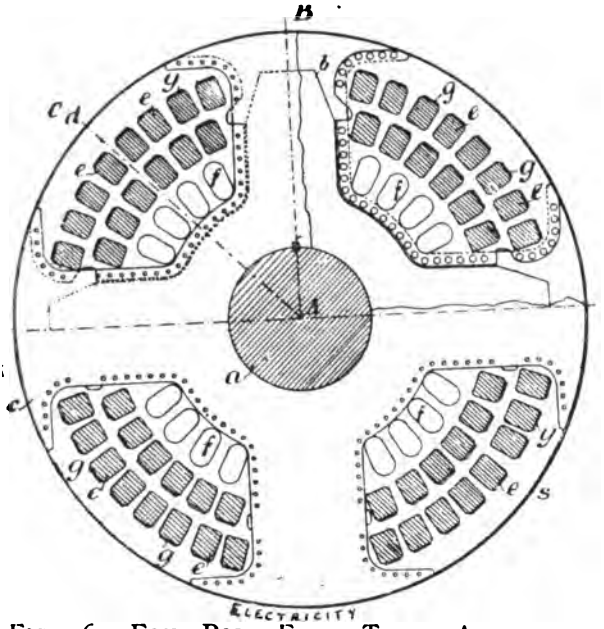

FIG. 96.—FOUR-POLE FIELD TURBO ALTERNATOR (PARSONS).

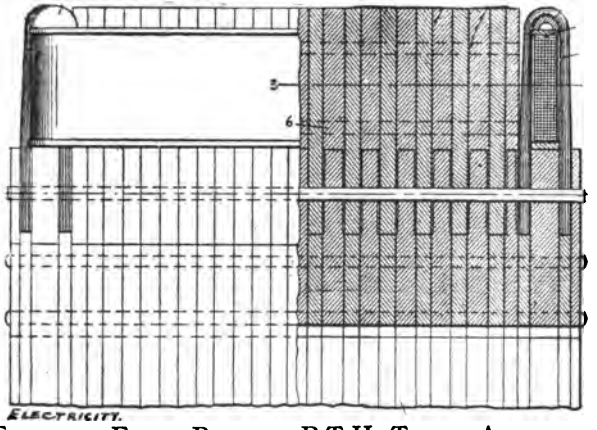

FIG. 97.—FIELD POLE OF B.T.H. TURBO ALTERNATOR.

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Fig. 98 shows a stamping for the magnet core of the pole shown, Fig. 97.

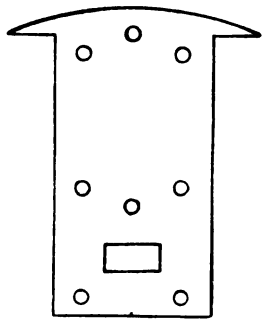

FIG. 98.—STAMPING OF B.T.H. TURBO ALTERNATOR.

Fig. 99 shows a four-pole field for a Lahmeyer turbo-alternator. The method of fixing the winding is somewhat similar to Fig. 93, though the winding is arranged rather differently. The method of supporting the coils, and at the same time covering up the ends to present a smooth surface and so reduce windage will be clear from the section.

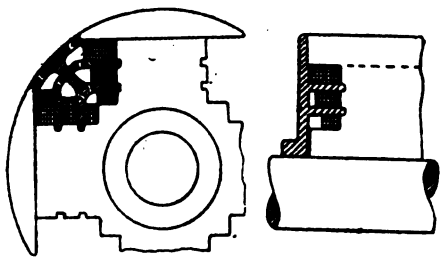

FIG. 99.—FIELD OF LAHMEYER TURBO ALTERNATOR.

The suitability of the inductor alternator for driving by steam turbines has been referred to and Figs. 100 and 101 are therefore interesting as almost the only

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example of this class of machine applied to the purpose. The manufacturers, M.M. Sautter Harlé et Cie., exhibited a similar machine at the Paris Exhibition of 1900, but it was arranged for belt driving. With the more extended use of the steam turbine the suitability of this design became apparent, and as they had acquired the Rateau turbine patents they proceeded to standardise this type of machine, for direct connection thereto.

It will be seen that this turbo alternator has the two exciting coils concentric with the shaft. The magnetic circuit, is, as will be seen, peculiar, consisting of one main iron body with projecting poles, which are more clearly seen in section (Fig. 101). There is an air gap at the main

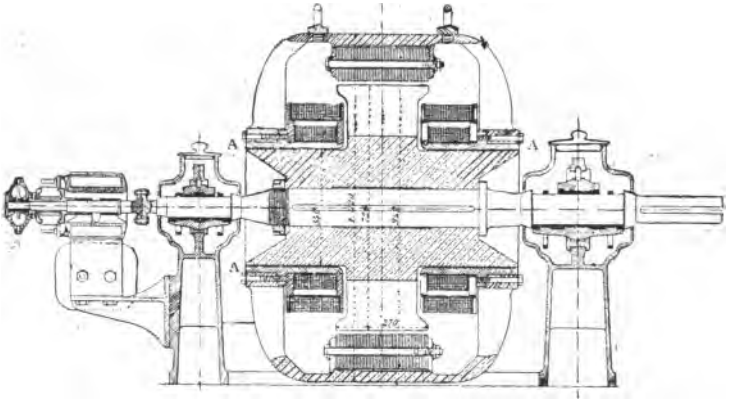

FIG. 100.—SAUTTER HARLE INDUCTOR ALTERNATOR FOR DIRECT CONNECTION TO STEAM TURBINES.

polar projection, and as the magnetic circuit is completed through the sides of the inductor, the flux after it passes across the main air gap and through the armature core, divides and returns down the side of the frame and across the small air gaps, A. (Fig. 100). The moving part (inductor) is the shaded portion on the shaft, and also the polar projections, the field winding being stationary. The arrangement of the polar projections

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and armature slots will be clear from the section (Fig. 101).

The fixed armature presents no points of interest, as the windings are identical with that described for slow speed machines, there being, of course, fewer groups and often more slots per pole and phase, as there are only two, four, or six field poles.

The excitation voltage is generally kept low in the case of turbo alternators, considerably below that usual with slow speed generators. This is due to the

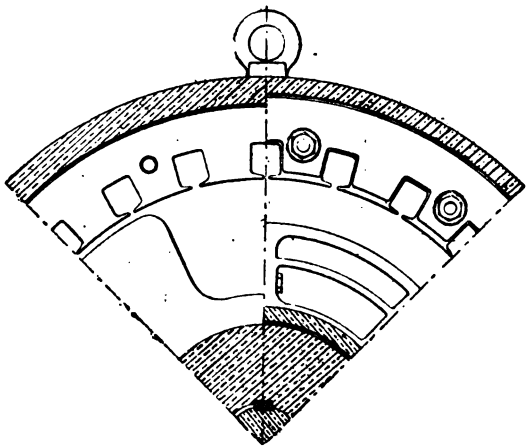

FIG. 101.

desirability of keeping the voltage per turn very low, as the mechanical stress between each layer is considerable, without adding to these by electric stresses due to a high voltage. The voltage is generally 20 to 50 volts. The 1,500 kw. turbo alternators in the Neptune Bank Station of the Newcastle-on-Tyne Electric Supply Co. are excited at 30 volts, at which pressure the exciters are capable of supplying 210 amperes.

The slower speed alternators of large power which are coupled to Curtis turbines give good results, and the output coefficients of these machines, by reason of

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their more moderate speed, is much nearer the values given in Fig. 47. Indeed, it is often lower, owing to the fact that the speeds are more favourable to the economical utilisation of the materials, and to the fact that the active material need not be sacrificed to an exceptionally large number of ventilating ducts. As an instance of such slow speed machines, the 5,000 kw., 60 cycle, turbo alternators in Fourth Street Station, Boston, which generate at 12,000 volts, run at 514 revolutions per minute, and the revolving field has 14 poles. These machines are of the vertical type, shown in section Fig. 102, a type which has become associated with the General Electric Co., of U.S.A., and the British Thomson Houston Co. in England, who make the Curtis steam turbine. It should be noted that as the diameter of the field magnet increases, and with it the number of poles, the necessity of keeping the E.M.F. of the exciting current low disappears, owing to the reasons already detailed.

Examples of Turbo Alternators.—Fig. 102 shows a complete vertical turbo alternator by the British Thomson Houston Co., coupled to a Curtis steam turbine. The construction has already been detailed (Figs. 97 and 98), and need not be further dealt with.

Another vertical turbo alternator is shown in Fig. 103. This is by the Allgemeine Elektricitats Gesellschaft, Berlin, and the prime mover is a Reidler Stumpf turbine, now becoming pretty well known on the Continent. The output of the set shown is 500 kw. at 750 revolutions per minute. Some large sets have recently been constructed, and may be seen in operation at the Moabit station, Berlin Electricity Works. The field winding is held in position by the casting shown black in the section.

Figs. 104 and 105 show two views of Westinghouse turbo alternators; these have horizontal shafts for direct connection to Westinghouse Parsons turbines, and give an output of 3,500 kilowatts at 1,000 revolutions per minute. The ventilating ducts on the field poles and saucer-shaped discs covering the ends can easily be seen.

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These were referred to when describing the constructional details; so also was the Westinghouse method of winding the field magnets (Figs. 94 and 95).

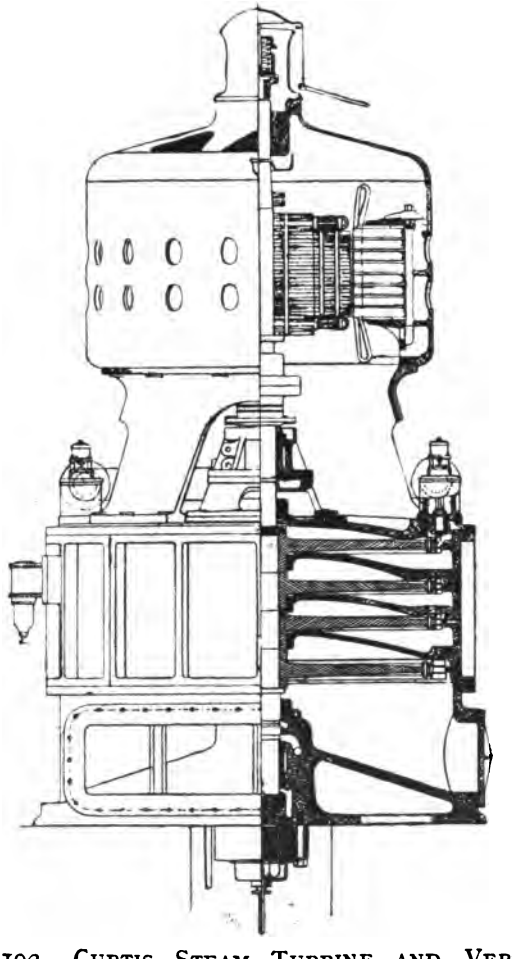

FIG. 102.—CURTIS STEAM TURBINE AND VERTICAL ALTERNATOR.

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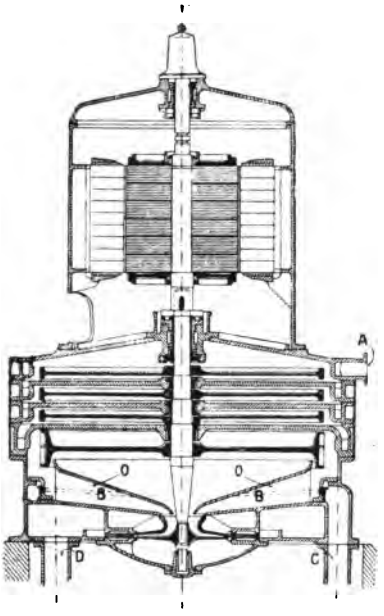

FIG. 103.—REIDLER STUMPF STEAM TURBINE AND VERTICAL ALTERNATOR.

Table XII. gives further particulars of this machine :—

TABLE XII.

Output	3,500 kilowatts.
Speed	1,000 revolutions per min.
Periodicity	33⅓ cycles per second.
Number of field poles ..	4
Diameter of rotating field	5 feet 7⅝ inches.
Length ,, ,, ..	3 ,, 9½ ,,
Pole pitch	53.11 inches,
Weight of rotating field..	23 tons.
,, fixed armature	48 ,,
Watts per revolution ..	3,500 watts
Output coefficient ..	58

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An interesting comparison between this turbo alternator and the Helios alternator, particulars of which are given in Table IX., may be made on the basis of the leading dimensions of the machines in question. This shows strongly the influence which high rotative speed has upon the design, notwithstanding the fact that the

FIG. 104.—FOUR-POLE FIELD WESTINGHOUSE TURBO ALTERNATOR.

periodicities differ sufficiently to make comparison of winding and constructional details inadvisable.

TABLE XIII.

	Turbo Alternator. Westinghouse.	Flywheel Alternator. Helios.
Speed	1,000 revs.	71½ revs.
Output	3,500 kw.	3,000 kw.
Cycles per second	33⅓	50
Number of poles	4	84
Pole pitch	53.1 ins.	12 ins.
Angular velocity of field magnet	17,650 feet per minute	6,000 feet per minute.
Weight of field ..	23 tons	74 tons.
„ „ armature	48 „	78½ „
Watts per revolution ..	3,500	42,000
Output coefficient ..	58	31½

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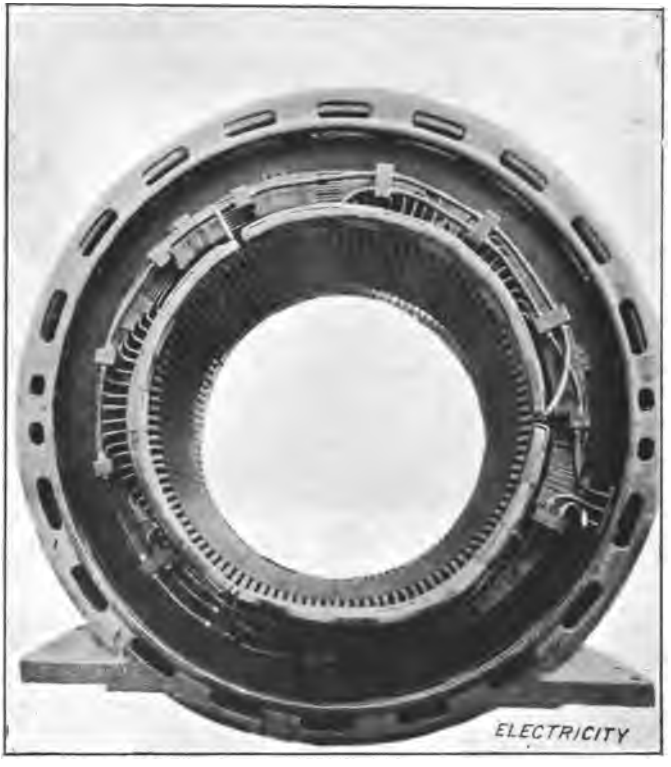

FIG. 105.—ARMATURE FRAME OF 3,500 KW. TURBO ALTERNATOR, NEASDEN POWER STATION, METROPOLITAN RAILWAY.

Fig. 106 shows one of the 2,000 kilowatt alternators supplied by Messrs. C. A. Parsons and Co. to the Newcastle-on-Tyne Electric Supply Co. It generates at 6,000 volts, and has a periodicity of 40 cycles per second. There are three such sets in the Carville Station of this Company.

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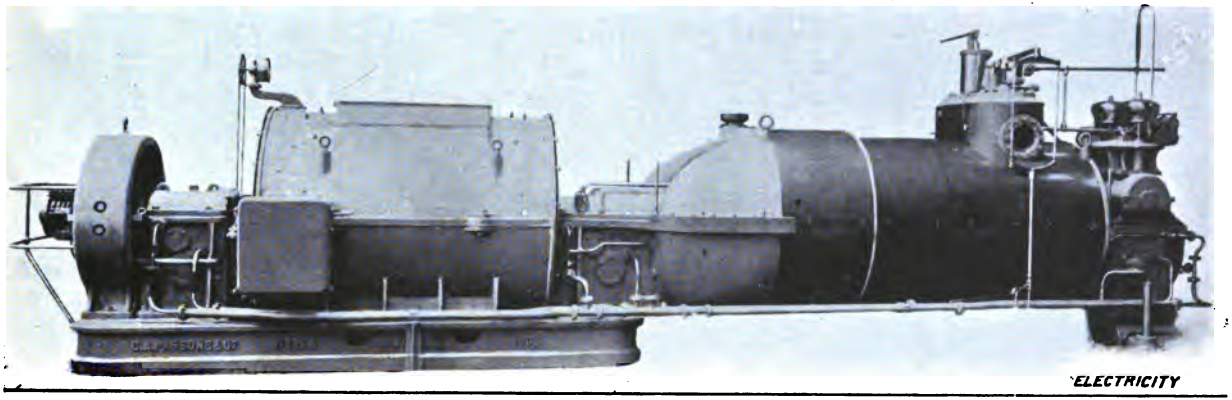

FIG. 106.—2,000 KILOWATT 3-PHASE TURBO ALTERNATOR, NEWCASTLE-ON-TYNE ELECTRICITY SUPPLY.

CHAPTER XVIII.

Synchronous Motors.

Closely allied to, and in most respects identical with, the polyphase generator, is the synchronous motor. It is to all intents and purposes a generator whose functions have been reversed for the time being, and, instead of giving out electrical energy when driven, it absorbs electrical energy and does mechanical work. Unlike a direct current shunt dynamo, which is equally reversible, its speed is independent of the load and impressed voltage (only within certain limits of the latter). The speed is fixed by the periodicity, and they possess the grave disadvantage that they are not in the ordinary sense of the term self-starting. They can be made self-starting, but this property involves certain features in design or certain starting arrangements which necessitate the introduction of auxiliary starting apparatus, generally absent in the case of the non-synchronous motor. The chief reason why they are used is the fact that at the proper excitation they have a power factor nearly unity, and consequently for the same capital invested in mains and machinery a little more can be got out of it than in the case of a non-synchronous equipment. A more valuable feature is that by varying the excitation they can be employed to compensate for the lagging currents due to inductive apparatus, and thus get rid of the adverse influence of the wattless component upon the pressure regulation of the generators, the line drop, and the overload capacity of the motors working on the system, for it must be kept in mind that as the output of alternate current motors varies as the square of the impressed pressure, very serious trouble may result from the lowering of the terminal voltage when an overload comes on.

Over-excited synchronous motors are frequently employed for the purpose of compensating for the lagging currents due to a large number of induction motors. In several large plants in the Western States of America

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one fair-sized synchronous motor has been found to give excellent results when installed for this purpose among a number of induction motors, which, by the way, scarcely influences its performance, so far as capacity for mechanical work is concerned.

The sphere in which synchronous motors will be found most useful, and, indeed, where they are almost invariably used, is in the sub-stations of large electric supply systems, where the requisite skill for the satisfactory operation of these machines is easily found. The necessity for careful synchronising and paralleling makes their use inadvisable in a factory or similar place, and, indeed, nothing can generally be gained by introducing them, except, perhaps, in spinning and weaving mills, where absolutely constant speed is necessary, though even there the small variation in the speed of induction motors will not be found of any serious importance.

No reference will be made to the construction of these machines; they are identical in all details with the generators just described, but reference to their starting and running characteristics will be necessary.

Starting.—The fact that they are not, in the ordinary sense of the term, self-starting, has already been pointed out. Any synchronous motor will, however, start up from the alternate current side if supplied with enough current; all that is necessary is to open the field switch, *i.e.*, leave the machine unexcited and switch the line current on; owing to the lag of the magnetisation in the poles, behind the magneto-motive force of the armature, and to a lesser extent the eddy currents in the pole faces sufficient torque is exerted to bring the machine up to almost synchronous speed, when the field current may be switched on and adjusted. Where the poles are fitted with damping coils (amortisseurs) the machine comes up to speed more easily, as then it is almost analogous to an induction motor with a short-circuited (squirrel cage) rotor. The large amount of starting current taken when starting in this manner—about two and a half to four times the full load amperes—makes it objectionable

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wing to the disturbance of the line pressure, hence the machine may be, and is, often started by means of a s tarting compensator (auto-transformer), as shown in Fig. 107.

This consists of a choking coil connected as sho wn, which, while giving half the pressure at the armature of the synchronous motor, and about twice the normal current, taking only full load current and normal E.M.F. from the line, enables the machine to be run up, with a smaller current taken *from the line* than might otherwise be the case, and therefore one of the most serious objections to the self-starting synchronous motor is eliminated. It should be noted that the action of the

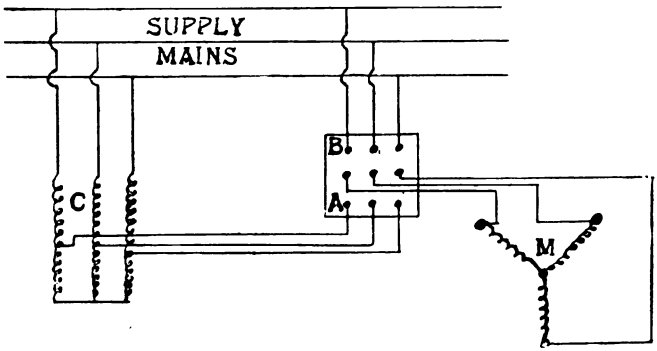

FIG. 107.

compensator, although resembling a choking coil, is that of a true transformer. This may be taken for granted just now, as the starting compensator will be more fully dealt with when the starting of induction motors is under consideration. The three-pole change-over switch is on "A" at starting, and when the speed is sufficiently great it is thrown over to "B," thus putting the line E.M.F. direct on to the motor.

Another method of starting is to run the machine up to speed by means of a small induction motor having in some cases *fewer* poles than the synchronous machine, thus enabling synchronous speed to be easily attained.

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This small motor need only have a capacity of about 10 per cent. of the full load of the synchronous machine, and may be mounted on a bracket carried on one bearing, just as the exciter is carried. This is common practice with rotatory converters, as will be afterwards described.

If the synchronous motor drives a direct current generator in a sub-station—which is about the only place in which one finds synchronous motors—it is usual to start the set up from the direct current side by using the generator as a motor, obtaining the current either from the direct current bus bars, or a battery, where one is installed. Starting from the direct current side is, in such cases, very convenient practice; but it must not be forgotten that it may be necessary to start from the alternate current side, as, for instance, in a case where no battery is installed and the direct current bus bars may at certain times be dead, as when a tramway system is shut down. Then, of course, the first set must be started from the alternate current side.

Synchronous motors usually resemble generators in that they have a small direct current generator carried on a bracket on one bearing, as an exciter; sometimes, however, in sub-stations, they are excited from the direct current bus bars, or from a small direct current generator driven by an induction motor. The latter is not often used.

Running.—The performance of synchronous motors when running exhibits some very important characteristics. As has already been pointed out, one of their valuable features is their property, when over excited, of compensating for lagging currents induced by other types of apparatus. This property is due to the fact that under normal conditions, *i.e.*, proper excitation, the vectorial sum of the ohmic drop, the reactance drop, and the back E.M.F. of the motor, should equal the terminal pressure. Should, however, the excitation be reduced, the armature current will rise, and there will be a considerable wattless component *lagging behind* the terminal pressure; if, however, it is lagging

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behind the applied (terminal) pressure it will obviously *lead* the armature back E.M.F., and therefore strengthen the motor field to maintain the sum of the foregoing voltages equal to the terminal pressure.

If, on the other hand, the converse is the case, and the exciting current is increased, the back E.M.F. is now greater, and the sum of this, and the ohmic and reactive drop is greater than the impressed pressure and the motor now takes a current which, however, is leading, and if it is a leading current in relation to the supply E.M.F. it must lag in relation to the back E.M.F. of the motor, and therefore demagnetize its field in order to restore the balance.

It should be noted that while variations in excitation influence the apparent watts taken by the motor, it influences the true watts taken only to a small extent, due only to the growth of $C^2 \times R$ losses with the greater current. The efficiency of the machine is therefore only slightly reduced, though the variations in the power factor are obviously considerable. The influence of variations of field current is shown in Fig. 108, and it will be seen that wide variations of armature current can be obtained if necessary. It will also be noted that if the motor is adjusted for minimum armature current, it is unnecessary to make further adjustments with variations of load, for, as will be seen, the field excitation which corresponds to minimum armature current at light load is almost the same for other loads. The two sides of the "V" curve are slightly different; one is straight, while the other is convex. This is characteristic of practically all such curves when obtained experimentally, though it appears that theoretically one leg should be convex and the other concave; the practical difference is explained by the influence of the low power factor of the lagging current and also to armature reaction. Motors operating through a line having high resistance, or whose armature has high resistance, will have the broken line A bending towards the left, while if there is considerable reactance and smaller resistance, the line A will bend towards the right; the latter is the more common

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characteristic of most synchronous motors, though the line is, as a rule, very nearly straight.

The shape of the "V" curve is a good index of the characteristics of the motor; if it is broad, *i.e.*, the two sides diverge rapidly, then the machine will obviously require a small variation of exciting current to maintain a power factor of unity over a wide range of load; it also denotes that the machine will be fairly satisfactory in parallel with others, and has

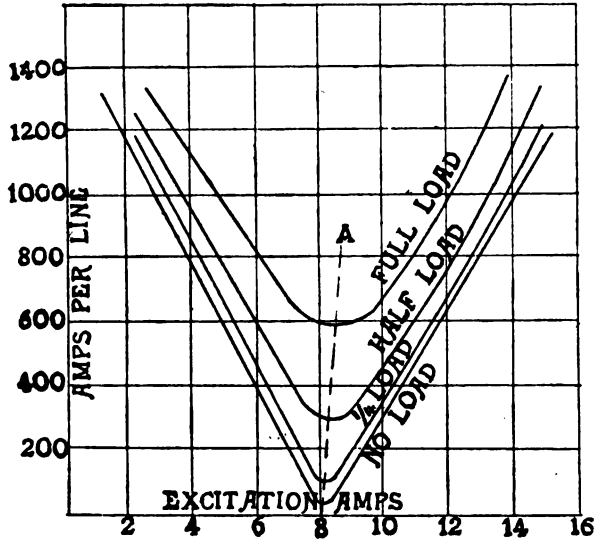

FIG. 108.

considerable overload capacity. On the other hand, a machine giving a "V" curve with steep sides must obviously be much more closely watched when running, as it has small overload capacity, and not very satisfactory paralleling properties, except with a carefully adjusted exciting current. When taking "V" curves the motor, when on load, becomes unstable at the top of the curves and frequently drops out of step and stops.

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CHAPTER XIX.

Rotatory Converters.

Perhaps no class of machine for converting alternating into direct current is more popular than the rotatory converter, and deservedly so, for it is cheap and efficient and with reasonable attention is no less satisfactory than any other type of sub-station apparatus. There has been, and still is, some prejudice against this type of apparatus, but it exists chiefly among those who have had least experience of such machines, and, as the author pointed out in a paper read to the Newcastle Section of the Institution of Electrical Engineers,* the claims of the rotatory converter on the score of efficiency and low first cost justify its adoption in most cases to the entire exclusion of motor generators.

The principal reason for its superiority is that, reduced to its lowest terms, it is merely a revolving commutator, *i.e.*, the alternating currents are merely rectified, not transformed, first into mechanical power, then back into electrical power, as in the case of a motor generator. It is to this fact that the converter owes its superiority, a superiority more readily recognised on the other side of the Atlantic than here.

If one studies the distribution of pressure round the commutator of an ordinary bi-polar direct current dynamo, it will be found that if a curve of pressure is plotted, it will be similar to Fig. 109, that is, the + brush will be at a potential difference of, say, 220 volts to the negative brush, and if the pressure is laid out on squared paper as the ordinates, and the segments around the commutator as abscissæ, the diagram of E.M.F. will be shown as Fig. 110, which, it will be seen, is a wave closely resembling a rectified alternate current wave. Suppose we fitted two slip rings, "S," to the machine, each ring connected to diametrically opposite points of the armature, C and D, Fig. 111. If we

* *Journal of the Institution of Electrical Engineers*, Vol. XXXI., pp. 1122-1143.

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drive it with a belt as we formerly did, we could, of course, get direct current from the commutator as before, but we can also get alternating current if we place brushes on the slip rings. It will be obvious that if the points C and D, shown in Fig. 111, are connected to slip

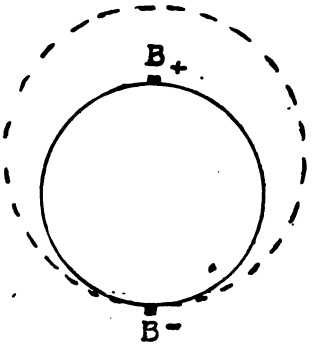

FIG. 109.

rings, we shall have an alternating current whose wave of E.M.F. for a complete revolution will be similar to the wave shown in Fig. 112, half a wave being generated during half a revolution, just as has been ex-

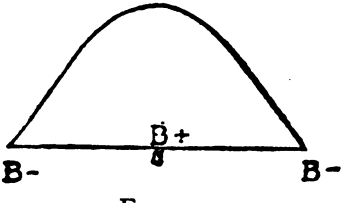

FIG. 110.

DIAGRAM SHOWING PRINCIPLE OF ROTATORY CONVERTER.

plained in Chapter II., Figs. 2 and 3, in which the elementary alternator was discussed. It will also be obvious that the maximum height of this wave will be equal to the maximum E.M.F. which the machine would give as a continuous current machine; the effec-

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tive value of the alternate E.M.F. will therefore bear the same ratio to the direct current voltage as the effective E.M.F. bears to the maximum E.M.F. of an alternator, which is, assuming a sine curve, ·707 of its maximum

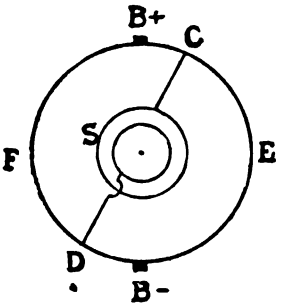

FIG. 111.—TWO-POLE SINGLE PHASE CONVERTER.

value. This applies to single phase converters only. The machine to which we have already referred will either give the whole of its output as direct current, the whole of its output as single-phase alternating

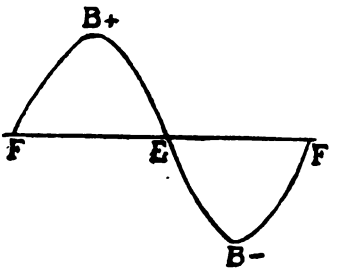

FIG. 112.

(assuming its fields either separately excited or excited from the direct current side), or if supplied with single-phase alternating current, will give nearly the whole of the power input as direct current at the commutator or it will, if supplied with direct current, give single-

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phase alternate current, and thus become an inverted converter. We now have the rotatory converter in its simplest form, and we also see that the same machine is essentially a double current generator. If instead of

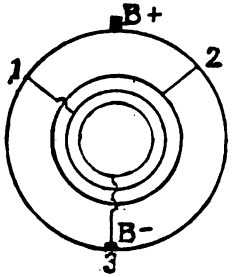

FIG. 113.—TWO-POLE THREE PHASE CONVERTER.

single-phase we make the machine a three-phase converter by connecting three points to the armature winding, with three slip-rings, as shown Fig. 113, the ratio of E.M.F. is altered. We formerly had half of the

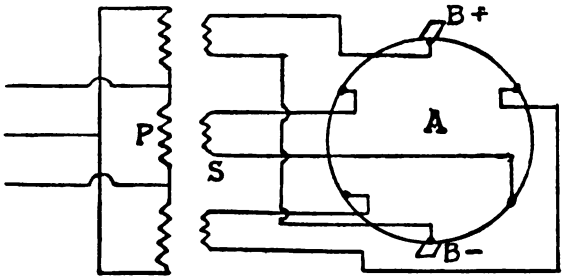

FIG. 114.— CONNECTIONS OF SIX-PHASE CONVERTER, DIAMETRICAL CONNECTION.

armature winding between each connection, and it was apparent that the maximum value of the alternate current (the peak of the E.M.F. curve) could not be otherwise than equal to the direct current E.M.F. In

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the case of a three-phase converter, where the windings are connected to points differing by 60 degrees, the effective voltage on the three-phase side will be ·707 × sine 60° = .612 of the maximum value of the direct current. For two-phase it is obviously the same as for single-phase, as the converter then consists merely of two single-phase connections made to points differing 90 degrees. The values given differ in individual machines, depending to some extent upon the ratio of pole-face to pole-pitch, for these vary with many types of converter. Table XIV. gives the ratios of direct E.M.F. to the various classes of alternating E.M.F. for three different ratios of pole-breadth to pole-pitch :—

TABLE XIV.—VOLTAGE AT POLYPHASE SIDE OF CONVERTER FOR 100 VOLTS, DIRECT CURRENT.

Class of current.	Pole faces Covering 70% of pole-pitch.	66% of pole-pitch.	50% of pole-pitch.
Single-phase	70·7	75	82
Two-phase	70·7	75	82
Three-phase ..	61·2	64	71
Six-phase with diametrical connection	71	76	83
Six-phase with delta connection	61	64	72

With diametrical connection (Fig. 114) the voltage ratios must naturally be the same as for single-phase ; this will be apparent in comparing Fig. 114 with Figs. 110 and 112.

Six-phase delta connection is merely a double delta, as shown diagramatically (Fig. 115). The latter is not often used as the higher E.M.F. on the secondary of the transformer (to slip rings) available with six-phase diametrical connection enables cables of smaller section to be used between the secondaries of the transformers and the slip rings of the converter.

It will be seen that the ratio of conversion, while fixed for any given machine, differs with the design. Machines with the poles covering 70 per cent. of the pole

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pitch are most usual and give approximately a sine curve, the others give a peaked wave.

On referring to the diagrams, Figs. 111 and 114, it will be seen that at certain points in the rotation of the armature the current does not pass through the machine at all, but simply from the alternate current slip-ring direct to the brush, and out to the direct current side; for instance, when point C, Fig. 111, passes the brush B+ no current flows in the windings. This occurs in the case of a single-phase converter twice per revolution, in the case of a two-phase converter four times per revolution, in a three-phase converter three times per revolution, and so on. From this we see that a rotatory converter has, depending upon the number of phases, no current at all in the winding at certain points of a revolution. This explains one reason why a rotatory converter, as such, will give much more current than it would if driven as a direct current generator, with the same $C^2 \times R$ loss, and temperature rise. Further, as we have already seen, the current in the armature of a two-phase two-pole converter is zero four times per revolution, while in the case of a three-phase converter it is zero only three times, and although the output of the two-phase converter may be taken greater than that of the three-phase converter, full advantage cannot be taken of this, because of the fact that the $C^2 \times R$ losses are not the only losses which take place; the iron losses contribute about half, but these do not vary, consequently the output is not quite so great as might at first sight appear likely. The following figures give the relative output for various types of converters, the outputs being figured for equal armature heating. The direct current output being taken as = 1.

TABLE XV.—OUTPUT OF ROTATORY CONVERTERS.

	One phase.	Two phase.	Three phase.	Four phase.	Six phase.
Output for same temperature limit as direct current generator.	·85	1·64	1·34	1·64	1·96

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The advantages which six-phase converters possess can be easily seen, and their popularity is therefore not so remarkable, considering the advantage of 45 per cent. additional output with small increase of complication on the alternate current side.

In the case of two-phase converters and six-phase converters with diametrical connections (Fig. 114), the lines between the secondary of the transformers and the slip rings must be fitted with switches for opening the circuit, if it is intended to start these from the direct current side, as otherwise it is apparent that there is a particular point where if the brushes are on the segment connected thereto, the transformer secondary practically short circuits the direct current brushes. In other cases, or where starting is effected by an induction motor on the converter shaft, the secondaries need not, and often are not opened, not even provided with switches, high pressure primary switches and direct current switches being all that is provided.

The connections of a so-called six-phase rotatory converter are shown in Fig. 114, P being the primary of the transformer, S the secondary, A the converter armature, B + and B — the direct current brushes. It will be seen that such a machine is really a three-phase converter with six slip-rings, the essential point being to have as many points as possible where the armature current is zero, *i.e.*, merely passes from slip-ring to brush without passing through the windings. The diagram is, of course, for a two-pole converter, and the six slip-rings are omitted to make the drawing less complex, the connections from the secondary, S, to the winding on the armature, A, being taken direct. In practice each of the six connections has one slip-ring.

It must be kept in mind that the voltage ratio of conversion is fixed, and variations in power factor do not appreciably influence the current output on the direct current side. By varying the excitation very wide changes can be made in the current on the alternate current side, but no change on the direct current side. This will be clear from Table XVI, where the full output

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of a 250-kw. converter remains unaltered with very great changes in field amperes and consequently in power factor of alternating supply. This is due to the fact that in the case of a leading current, *i.e.*, over-excitation of the converter, the wattless component, while it leads the supply E.M.F. it must lag behind the back E.M.F. of the converter, that is, lag behind the internal E.M.F., and therefore exercise a demagnetising effect upon the converter field, the action being precisely as described for a syn-

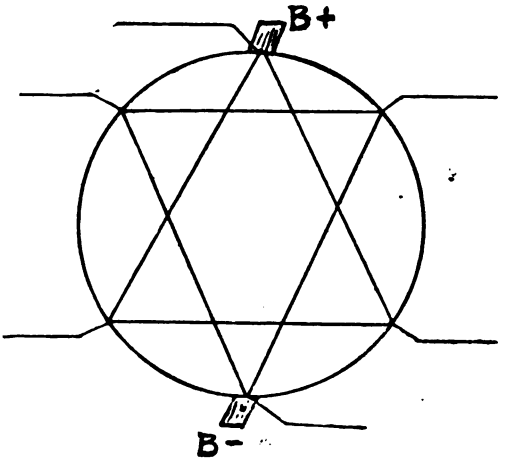

FIG. 115.—CONNECTIONS OF SIX PHASE CONVERTER, DOUBLE DELTA CONNECTION.

chronous motor under varying excitation. The converse is, of course, the case for an under-excited converter. Of course, the voltage ratio will alter to a greater or less extent, not due to any change in the ratio of conversion, but to the variation in the copper drop, due to changes in the line current, and, still more, to the influence of the lagging or leading component on the pressure regulation of the transformers and alternators.

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TABLE XVI.—250 KILOWATT CONVERTER WITH VARYING EXCITATION.

Excitation. Amperes.	Excitation. Kw.	Apparent Input Alternate current side. Kw.	Actual Input. Kw.	Power Factor.	Direct Current Output. Kw.	Efficiency of Conversion. %
1.5	.75	650	263.5	.4	248	93¾
2	1.0	536	262	.49	247.7	94½
3	1.5	375	261.2	.7	248.2	95
4	2.0	261	261	1.0	247.7	94½
5	2.5	335	261	.775	247.2	94¼
6	3.0	500	262	.52	244.7	93¼

It will be observed that in the last two cases the alternate current is leading.

The only other consideration influencing the output of these converters is the sparking limit, and as the armature reactions practically balance each other, *i.e.*, the reaction of the direct current on the field is neutralised by the action of the alternate current which is in opposition, the net result on the field is zero, hence the sparking limit is only that imposed by the permissible current density at the point of collection.

In the case of a double current generator, *i.e.*, an engine-driven converter, giving both alternate and direct current, the foregoing considerations do not apply, because here the armature does not have any points where the current is zero, and therefore the armature heating is due to the *sum* of the alternate and direct currents, while the armature reaction is also due to the sum of both currents. A little reflection will show that, just as in the case of a direct current motor generator with two commutators and a double-wound armature, the machine has practically no sparking limit, owing to the reaction of the dynamo and motor side being equal and opposite, and therefore cancelling each other; yet that machine as a generator, when driven with power and the output taken at both commutators may be a particularly bad machine. So far as sparking is concerned, exactly the same considerations apply to a rotatory converter and a double current generator.

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Viewed from the alternate current side a rotatory converter is practically a synchronous motor, and possesses every characteristic of such a machine as detailed in Chapter XVIII.; it will not therefore be necessary to again deal with the performance of the converter as a synchronous motor. The performance of the machine as an inverted converter should, however, be referred to at this point. As an ordinary converter, its speed is proportional to the periodicity and inversely proportional to the number of poles, and is invariable with an invariable periodicity ; it also possesses all the characteristics of a synchronous motor under varying excitation, but as an inverted converter, supplied with direct current and delivering alternating current, it possesses most of the characteristics of a direct current motor, and its speed is no longer fixed by the periodicity, but proportional to the E.M.F. of supply and the back E.M.F. generated in the armature.

So long as the power factor of the alternating current is unity the performance will be satisfactory enough, but with a lagging component the field is weakened ; and in order to maintain the balance between the back E.M.F. + the ohmic drop and the E.M.F. supplied, the speed of the machine will rise, as the decreased field flux results in a lower back E.M.F., and the machine will speed up till it runs away. As the increase in the frequency of the converter over the normal frequency of the line causes a still further increase in the lagging component, this effect is cumulative. On the other hand, with a leading current on the alternate side the field is strengthened and the speed of the converter drops. For this reason inverted converters are usually separately excited. Their chief use is to serve as a connecting link between the direct and alternating current plant in a tramway station, using alternating current for distant sections, feeding these through converter sub-stations, and having direct current generators for supplying sections close at hand without conversion.

In such cases the load on the alternate current side may sometimes be too small to warrant the running

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of a large polyphase generator, and the direct current is therefore passed through the converter, and transformed up to the line pressure. Inverted converters are used for this purpose by the London United Tramways, Dublin Tramways and others. In the latter town an ingenious arrangement is introduced to eliminate the possibility of the converter getting out of control through the demagnetising effect of the lagging currents. The converter, which is compound wound, has connected with its shaft an auxiliary converter which is supplied by current from two series transformers. By variations of the auxiliary field position this small converter is made to supply a compounding current when the power factor of the alternating current side of the main converter is less than unity, and so replace the ampere turns on the magnets lost through the armature reaction of the lagging component. The speed of the converter, it appears, can be maintained within three or four revolutions of the normal by this arrangement.

Rotatory converters are generally compound wound for feeding tramway and railway systems, and shunt wound for lighting circuits. A field resistance in series with the shunt winding enables such variations of the exciting current as are necessary to be obtained, and the exciting current is generally obtained from the direct current terminals (except when inverted). The result of compounding for a rise of pressure on the direct current side with increase of load is not due to any change in the ratio of conversion—this is fixed, but to the action of the machine as a synchronous motor when over excited producing a rise of pressure on the alternate current side, thus raising the pressure on the direct current side.

This action has been fully described in the section dealing with synchronous motors. In order to get a sufficiently wide range of compounding, say, 10 per cent., it is sometimes necessary, in the case of systems having small self-induction, to insert choking coils which slightly reduce the pressure applied to the slip-rings, the effect

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of the increase of the excitation due to the series turns, is by introducing a leading component to neutralise the self-induction of these choking coils, and so eliminate the pressure drop due to them, thus raising the pressure at the slip rings automatically; or the transformer supplying the converter may have several of the secondary turns connected to a switch, so that they may be switched out or in by hand, thus by varying the number of turns on the secondary, *i.e.*, altering the ratio of transformation of the transformer, obtain the necessary variation of impressed E.M.F.; the compounded converter is, however, most usual, particularly in tramway work. Among other methods is the use of a boosting transformer shown diagramatically (Fig. 116), where one phase only is shown, the primary P

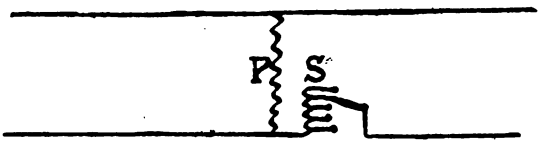

FIG 116.

is connected across the line and the secondary S in series with one line. If the E.M.F. on the left hand side is E then the E.M.F. on the left is E + Cs, where Cs is the E.M.F. of the secondary of the boosting transformer; the latter sometimes has the ends brought out to terminals, as shown, so that the amount of the boost can be regulated.

An ingenious modification of this has been installed in a number of places by the Westinghouse Company; it may be seen, among other places, in some of the substations of the North Metropolitan Electric Power Company, where they are hand controlled, while on the primary side of the 1,000 k.w. converters in several of the New York Edison Companies' stations, these induction regulators are worked by small induction motor worm geared to the movable secondary of the regulator, Fig. 117.

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Such a regulator consists essentially of a primary and secondary wound in slots, exactly as the primary and secondary of an induction motor (Fig. 129); the secondary is movable through that part of a revolution corresponding to one stator pole. From the connections

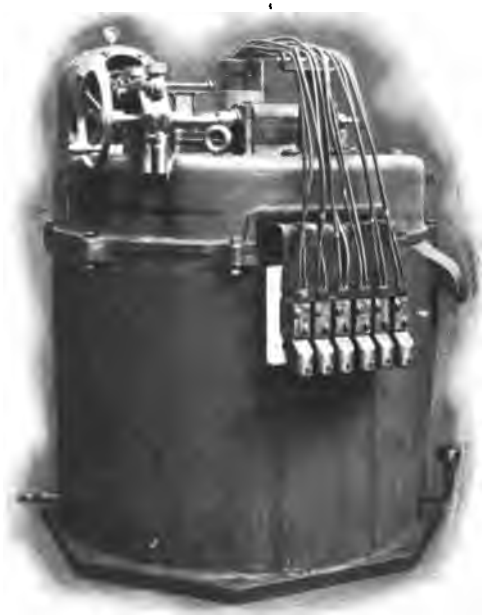

FIG. 117.—WESTINGHOUSE INDUCTION REGULATOR OPERATED BY SMALL INDUCTION MOTOR.

(Fig. 118 A and B) the arrangement and connections of the regulator will be clear. B shows the connections on one phase only, from which it will be apparent that it is connected essentially as a series transformer,

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the primary being on the movable core ; A shows the connections where P.P.P. are each of the phases of the primary and S.S.S. those of the secondary, while the triple pole switch on the leads to the converter are at s.s.s.

The apparatus is not really a transformer, what takes place is that the rotating fields due to the primary and secondary currents are both in the same direction, hence an E.M.F. is set up in the secondary due to the resultant field. The magnitude of this field

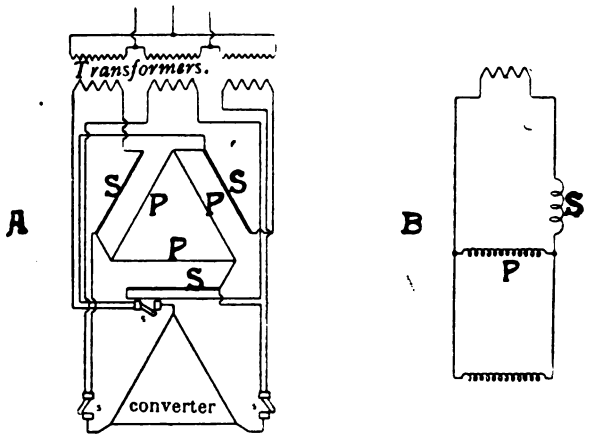

FIG. 118.

is unvarying if considered simply as a rotating field, and the secondary E.M.F. is therefore uninfluenced thereby, no matter what may be the position of the secondary with relation to the primary. The change in the secondary voltage is due to a change in the phase position of the resultant field, it being apparent that by moving the primary or secondary the phase position of the current in the latter is altered in its relation to the primary ; assume O—FS (Fig. 119) to be the field due to the secondary, while the primary field O—FP

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is along the same line, the polar position of primary and secondary being identical, that is the corresponding coils of each winding lie under each other, the resultant is therefore O—F1. The line voltage is 90 degrees later, and is O—E, while the induced secondary voltage is O—S1, and the resultant O—A is the load volts.

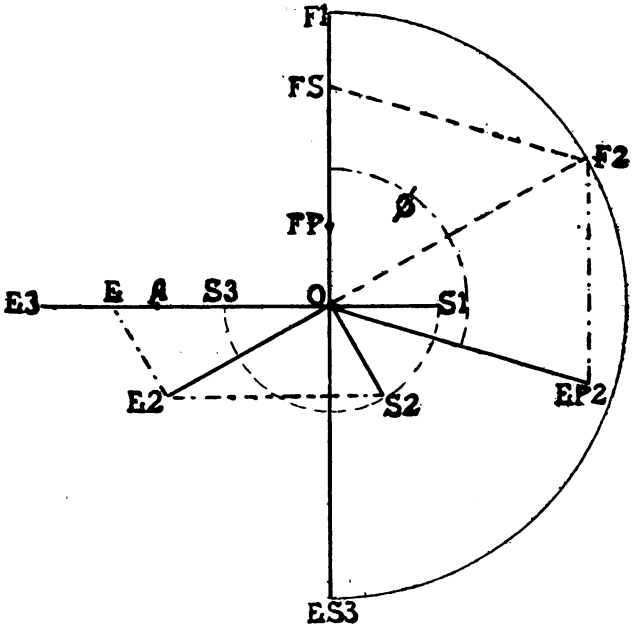

FIG. 119.

It the primary is moved through the angle FP, O EP2 the secondary field has less influence than at first, hence more primary current flows in order to keep the resultant field at its former value, owing to the withdrawal of some of the secondary influence, hence the resultant OF2 is of the same magnitude as before. The induced secondary voltage O S2 will be of the *same*

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magnitude as before and displaced 90 degrees from the resultant field; consequently the load volts are now OE2, *i.e.*, less than O E. Moving the primary or secondary still further, say 180 degrees, the secondary E.M.F., O–ES3 is shifted further in a clockwise direction, and is now directly opposed to the primary. The induced secondary volts O–S3 now lie along the line O-E, so that the resultant voltage is O E 3; O–S3, being added to the voltage O E. The influence of the primary and secondary voltages in producing a resultant is now clear, and also the fact that a movement of 180 degrees in the secondary produces a change from a maximum O–E3 to a minimum O–E2, O–E being an intermediate step.

Messrs. Cowans, Limited, make an excellent regulator patented by Messrs. Cowan and Still, which also gives a very gradual change in the E.M.F. It consists of a fixed and a moving core, Fig. 120, with part of the secondary wound on the fixed core in the slots r, and part on the moving core at S, while all of the primary is on this core. With the movable core in the position shown in the top figure, the magnetic induction which flows in the direction indicated by the broken arrows, links with the secondary in the slots r in the opposite direction to that part of the secondary S wound on the movable core, consequently the effect on the E.M.F. is zero.

The lower figure shows the movable core turned through 180 degrees. It is now apparent that the magnetic induction interlinked with the secondary on the movable core is in the same direction as that on the fixed core, hence the E.M.F. due to the two parts of the secondary winding is in the same direction, and a maximum. It is then in fact a true transformer with a primary, P, and a secondary, S, the amount of the boost being the ratio of transformation. In order to neutralise the induction of the secondary circuit when the movable core is in intermediate positions, shading coils, SC, are wound over the core. These are, of course, merely closed on themselves and add an insignificant amount to the loss in the transformer.

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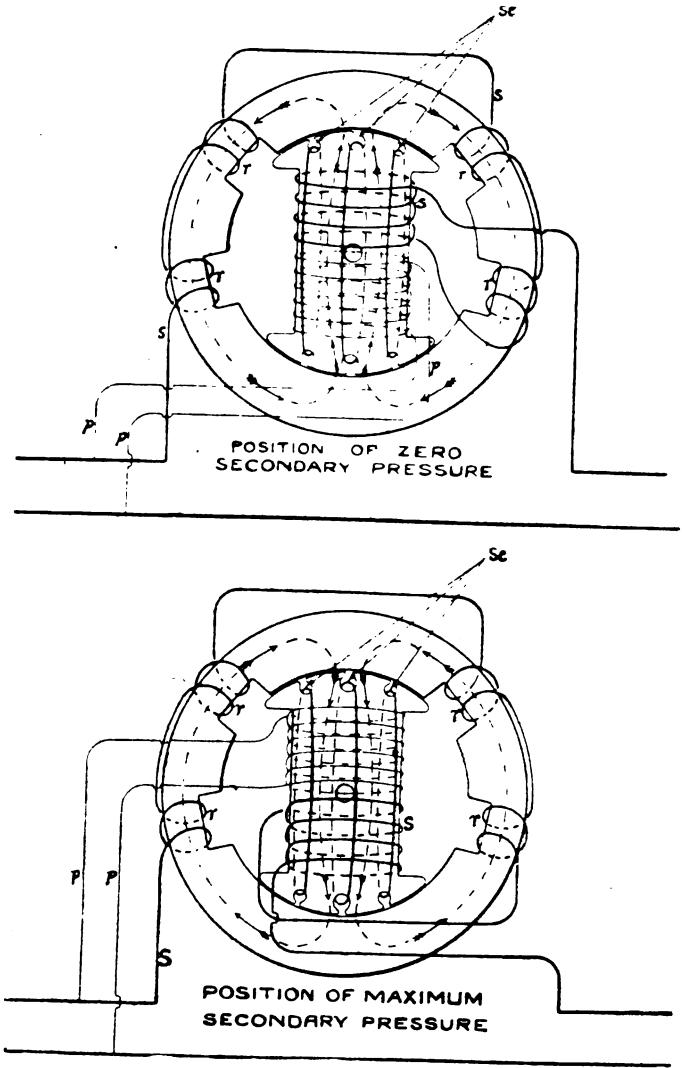

FIG. 120.—DIAGRAM OF CONNECTIONS. COWAN AND STILL REGULATING TRANSFORMER.

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Fig. 120A shows the external appearance of this transformer and also the worm gear for rotating the movable core.

Paralleling Converters.—All the precautions necessary in paralleling synchronous motors should be observed, and in addition it is necessary to see that the polarity of the direct current terminals coincides with that of the

FIG. 120A.—COWAN AND STILL REGULATING TRANSFORMER.

bus bars. This may be ascertained by means of a pole indicator connected to the direct current terminals.

Converters cannot be run in series on the direct current side and parallel on the alternate current side, such as in cases where they are supplying a three-wire secondary,

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they must be supplied from separate banks of transformers, or from transformers having secondaries wound as Fig. 121, where the converters are shown supplying a three-wire network It will be seen that as the

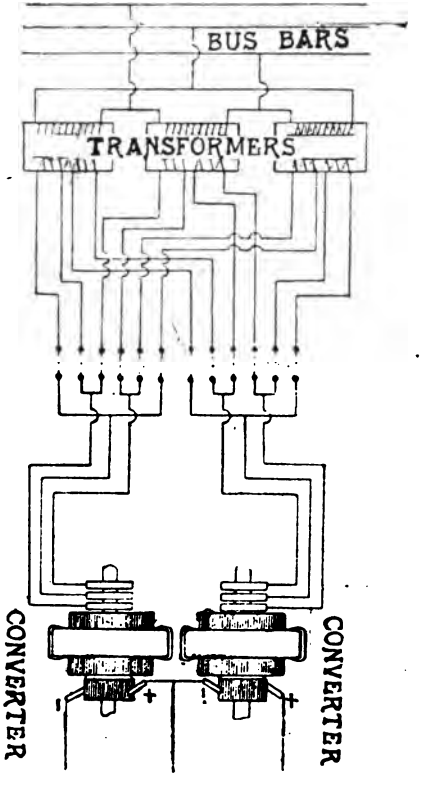

FIG. 121.

machines are connected together on the direct current side, a connection on the alternating current sides would cause a short circuit. Indeed, with converters of different design it is often more satisfactory for each to have its

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own bank of transformers when in parallel on both sides, as small differences in excitation or wave form cause considerable currents to be exchanged between them. They are also unsatisfactory when operating in parallel when there is considerable variation of the impressed voltage on the alternate current side, such as when supplied by alternators having bad regulation, or through a transmission line having considerable drop of pressure between no load and full load (*i.e.*, too little line copper). The drop of the impressed voltage below the back E.M.F. of the converter will cause the interchange of considerable current between the converters in parallel, or in the case of a single converter, the pumping will

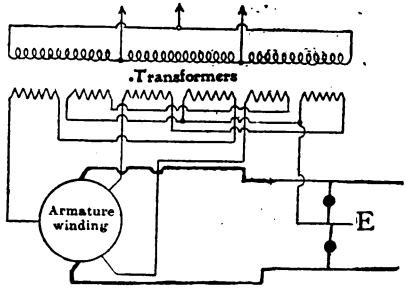

FIG. 122.

become so serious that the machine will swing out of step. Another method of supplying a three-wire network is shown in Fig. 122, where, with similar transformers, one converter only is employed, and the neutral of the Y connected secondaries, grounded, the converter then gives the E.M.F. of the outer wires on the three-wire network.

Rotatory converters are usually run on 25 cycle circuits. As has been shown when dealing with the parallel running of generators, low periodicities are favourable to satisfactory parallel running, as in the case of converters, they are influenced by the cyclic irregularity of the engines just as the main generators are,

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and the fact that they are synchronous machines makes their performance somewhat analagous to a machine driven through gearing, *i.e.*, there is little elasticity between the generator and the converter, and the converter follows, as far as its own momentum will allow it, every variation in speed, and therefore in periodicity, which takes place at the generating station.

High periodicities involve converters with a large number of poles if other questions, such as speed, and the mechanical considerations involved in it, are not to be overlooked, and it has already been shown how this influences the tendency of the machine to hunt. The momentum of the converter armature carries it beyond the magnitude of the original cyclic disturbance impressed upon it, and when that disturbance has subsided the armature tends to fall behind the original and correct phase position. This may go on for some time aided, perhaps, by the phase swinging of neighbouring converters till it swings out of step. Disturbances of this kind may influence a whole system. The advantage of converters with few poles is therefore apparent, and this necessitates low periodicity. It must not be supposed, however, that high periodicity converters are unsatisfactory. There is a very large installation of 50-cycle converters in the sub-stations of the Berlin Electricity Supply Co. (the Allgemeine Elektricitats Gesellschaft), which operates very satisfactorily with trifling exceptions, and in the Bilston sub-station of the Midland Electric Power Corporation there are a number of Westinghouse two-phase 50-cycle converters giving a satisfactory supply to the local tramways, while there are a number of 60-cycle converters in the sub-stations of the Seattle Electric Co., U.S.A., operated with current supplied from Snoqualmie Falls power station.*

In connecting up converters it is as well to note that the direct current side should have a tripping arrangement on the circuit breaker either in the shape of reverse current attachment, or as in a few American stations,

* "Transactions of the American Institute of Electrical Engineers," Vol. 21, p. 643.

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a small centrifugal on the converter shaft governor, which when the speed becomes excessive closes a tripping circuit on the circuit breaker, and so opens the direct current side. This is necessary, as should one converter, operating in parallel with a number of others, swing out of step the others will tend to drive it as a direct current motor with a weak field, and it would therefore develop a dangerous speed.

Construction.—Rotatory converters differ in one important point from synchronous motors; they have rotating armatures, and are identical in almost every respect with modern continuous current generators and

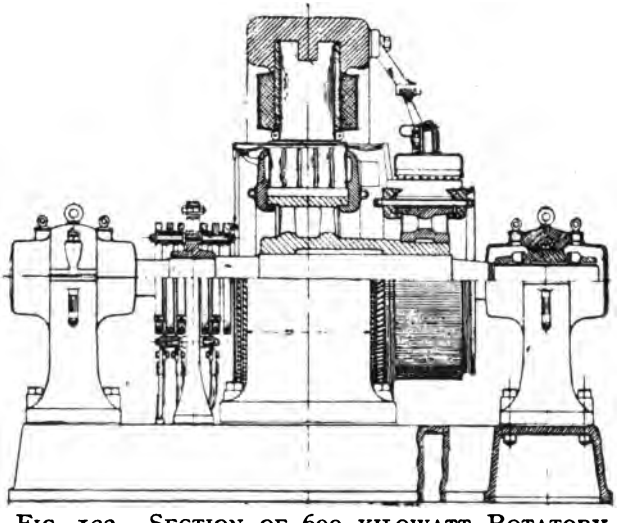

FIG. 123.—SECTION OF 600 KILOWATT ROTATORY CONVERTER.

motors; indeed, standard direct current apparatus is almost invariably supplied for such work. The principal difference is in fitting the poles with damping coils, such as has already been described under parallel running of the generators. These damping coils sometimes take the form of heavy copper rings which at the same time

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serve to support the field coils. Of course in standard direct current practice these bobbins or supports are absent, modern generators having their field coils merely wound on formers and taped, no bobbins being necessary. Figs. 123 and 124 show a standard 600-kw. rotatory converter by Dick Kerr and Co., in use in the sub-stations of the Liverpool-Southport Electric Railway; they are six-phase, have eight poles, and run at 375 revolutions per minute on a 25-cycle circuit, the E.M.F. on the direct current side is 600 to 650 volts. The complete machine weighs 18¼ tons, of this the arma-

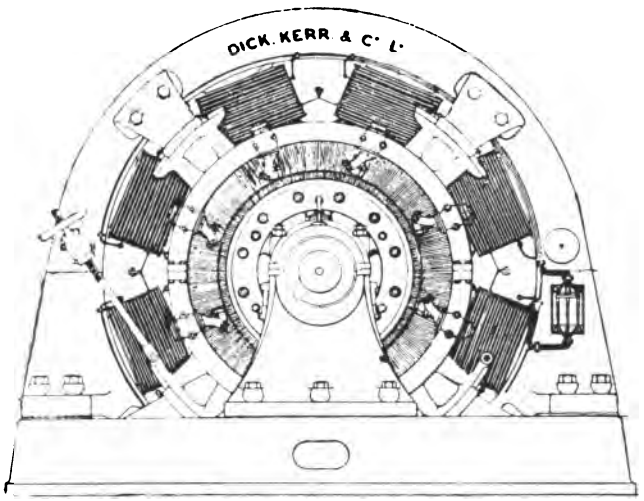

FIG. 124.—ELEVATION OF 600 K.W. ROTATORY CONVERTER.

ture accounts for 4½ tons, the remainder being field and bed-plate.

The constructional details, with the exception of the six slip-rings, correspond to Messrs. Dick Kerr's standard direct current machines, and as the constructional details of all converters is a matter more particularly

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of direct current practice, the reader wishing information on these points is referred to works on direct current machinery.

CHAPTER XX.

The Induction Motor.

The Induction Motor has now become one of the most common features of the industrial world. With the development of power distribution companies polyphase current can now be obtained in almost every place which aspires to any importance, as a manufacturing district. In addition, the supply systems in large cities in a few cases supply polyphase current to consumers, while others convert the polyphase current which they generate, to direct current, by means of motor generators; the induction motor has therefore become a familiar machine to many, though its action and general characteristics are by no means so generally understood as are direct current motors. The easiest way to enable the reader to grasp the principle of the induction motor is to describe it from some general principle not far removed from direct current machines and develop it along these lines till it becomes the induction motor of to-day.

Consider Fig. 125 as a four pole motor having radial poles like a direct current machine, but with A. B. in series on one phase, and C and D in series on another phase, the supply being two-phase as shown by the diagram Fig. 126. When the wave of phase I. has reached its maximum value, point I. on the wave, a magnetic field will be projected across the annular space, as indicated by the dotted lines. As it dies down and the wave due to phase II. becomes greater, the flux from A to B will decline and that due to C. D. increase till the point 2 is reached, where there is a current in both phases of the magnitude indicated on the diagram Fig. 126, and the resultant flux will now be as shown No. 2, an instant later phase II. has reached its maximum and phase I. is

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zero, the flux due to A.B. has now completely disappeared and that due to C.D. only remains; in other words, during one quarter of a cycle, that is the distance from the peak of the wave due to phase I. to that due to phase II., the flux due to the current in the two phases has travelled round one quarter of the circumference of the annular space in which the armature should be,

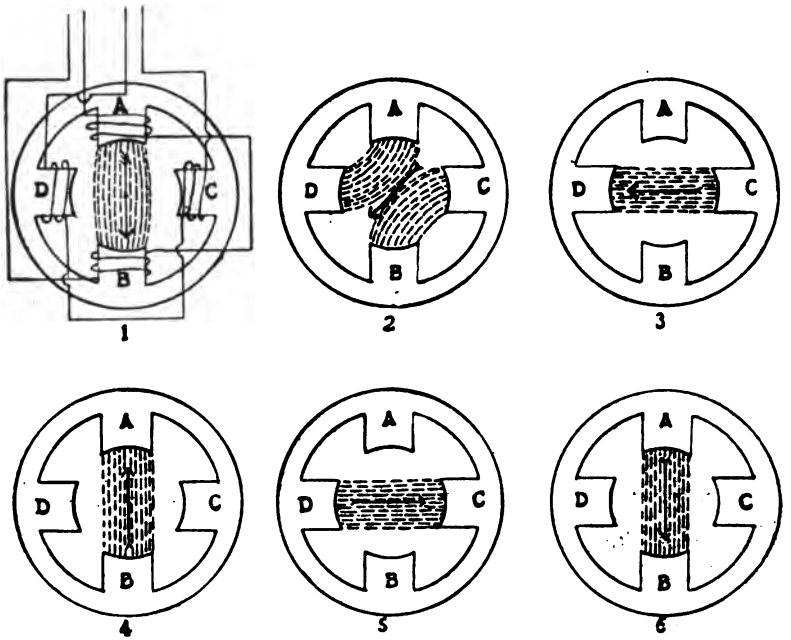

FIG. 125.—DIAGRAM ILLUSTRATING THE ACTION OF THE INDUCTION MOTOR.

and is in the position shown by the dotted flux No. 3. As the cycle proceeds phase II., which with phase I. has hitherto been in a + direction, now begins to decline, and phase I. begins to ascend in a negative direction—*i.e.*, the current in the winding on A and B has been reversed and the point marked 4 on the wave is reached,

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the magnetic field will now be projected across the gap in a direction opposite to that shown in No. 1. and is now in the direction indicated by the heavy arrow from B to A No. 4. During another fourth of a period the flux from B to A has declined and phase II. has reached its maximum—viz., point 5 on the wave, projecting its field across the gap from D to C, and another quarter period later phase I. has again reached its + maximum, point 6 on the wave, and projects its flux from A to B, in the direction of the heavy arrow No. 1 as at first illustrated. It will be seen that the magnetic field has rotated right round the annular space provided for the armature, that is, calling the

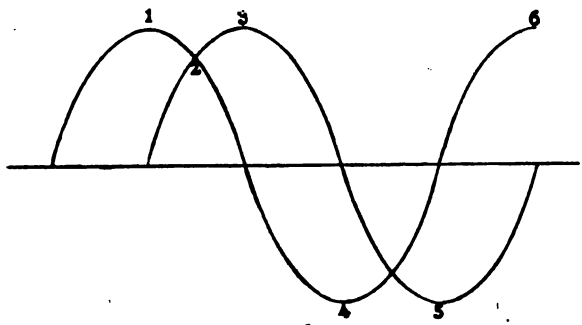

FIG. 126.

point of the arrow a North Pole, this pole has moved right round the space; were an armature inserted into the space in question, the rotation of the field flux would induce an E.M.F. and therefore a current in the winding. Consequently there would be a torque proportional to the watt component of the rotor current, and to the magnetic induction due to the field, the armature will therefore revolve at a speed almost proportional to the speed of the rotating field, which as will be apparent, is determined by the periodicity of the supply current. Its speed never actually reaches the speed of the rotating field, for if it did so the conductors on the armature would never cut the moving field flux, so no

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current would be induced in the armature wires; the armature therefore must move slower than the field flux, how much slower depends upon the load on the motor.

At light load the speed of the armature is nearly the same as that of the rotating field, but as the load grows, so also must the torque; and as this is proportional to the watt component of the armature current and to the magnetic induction of the field, one or other must be increased, the field flux is practically speaking nearly constant at all loads and the armature current only can be increased. This can be done by increasing the rate at which it cuts the field flux; this can be accomplished if the armature runs slower, for it is hardly necessary to point out that the lines of force cut by the armature conductors when the speed is exactly equal to that of the rotating field flux, is zero, and when the armature is at rest the lines of force cut by the conductors are a maximum, because the difference between the speed of the field and armature is maximum; there are also numerous intermediate points where various other values of the flux cutting the armature conductors may be obtained.

Under ordinary working conditions it may be assumed that the difference in speed between the rotor and stator field is about $\frac{1}{8}$ to $\frac{1}{4}$ per cent. at light load and about four to ten per cent, at full load—*i.e.*, the difference in speed necessary to cause the armature conductors to cut sufficient magnetic flux to induce an E.M.F. in the armature winding large enough to cause the necessary current to flow, in order to produce the torque required and also sufficient E.M.F. to overcome the rotor resistance and self-induction, is only one eighth to one quarter of a revolution in each hundred at light load, but it may reach ten revolutions in each hundred at full load. Much, of course, depends upon the size of the motor. This difference between the speed of the field flux and the armature is termed the "slip." It will be seen that the armature, which may consist of a drum armature with copper bars in each slot, connected at the

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ends to a ring as in Fig. 127, is in no way connected to the supply circuit; only the field winding is connected thereto, and the relation of the field to the armature is much the same as the primary and secondary of a transformer.

As the load on the motor grows, the slip increases, and with this increase in slip there is a consequent growth in the armature current. This increase in the armature current tends, owing to reaction, to reduce the total magnetic flux and therefore reduce the back E.M.F. of the field winding, as it reduces the self-induction of the field, this being proportional to the magnetic flux interlinked with it. This reduction in the back E.M.F. of the field winding enables more current to flow in from the line, and thus the field takes a greater current from

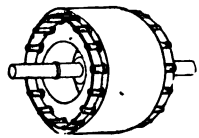

FIG. 127.

the supply, this increased current being proportional to the reduction of its own back E.M.F. of self-induction, the latter is reduced by the growth of the armature current, the armature current is, in turn, increased by the increase in the slip which is proportional to the load on the motor. This explains why an increase in the load on an induction motor causes it to take more current from the supply system.

The last elementary stage is to abolish the terms field and armature as applied to an induction motor, and substitute "stator" and "rotor" respectively, the reason being that "field" and "armature" are not strictly applicable, the transformer-like action between the field and armature making the terms "primary" and "secondary" more correct. This, however, may lead to confusion as the secondary is a moving mass, and Professor S. P. Thompson was, I believe, the

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originator of the terms "stator" and "rotor," which have now come into very general use, though the terms primary and secondary are in common use on the Continent and in the United States. The fact that the secondary obtains its current by the inductive action of the primary is the source of the term "induction

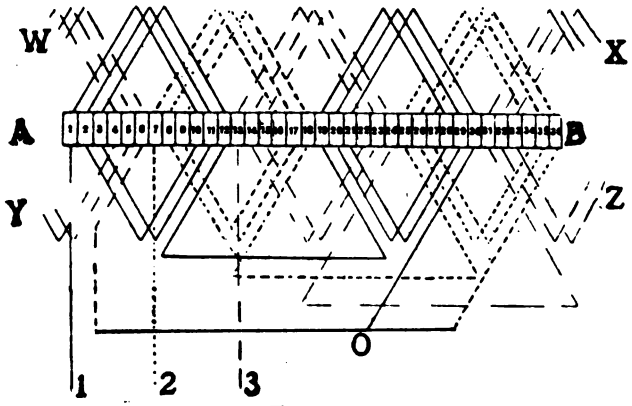

FIG. 128.

motor." To return to Fig. 125, the radial poles shown correspond to one slot per pole and phase, but it is usual in induction motor design to have the inner surface of the stator smooth and scatter the winding into several slots per pole, each slot similar to that in the armature shown in Figs. 11 and 17 (Chapters V. and VI). This leaves a uniform path for the magnetic induction as it passes round the inner surface of the stator, and moreover reduces the humming of the machine in proportion to the reduction in the width of the mouth of these slots; (there are, of course, other considerations). We therefore have a stator resembling Fig. 128, where only two poles have been wound this time for three phases; but instead of very pronounced radial poles, as in Fig. 125, the turns of stator wire are distributed in six slots per pole, and the interior is, practically speaking, smooth. The stator

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FIG. 129—BRUSH ELECTRICAL ENGINEERING CO.'S THREE-PHASE INDUCTION MOTOR WITH ROTOR REMOVED 4 POLES, 8 STATOR SLOTS PER POLE AND PHASE.

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has been drawn extended out flat to make the winding clear; but, of course, the ends A and B are joined together, making the circular stator, W to X, and Y to Z. In practice the various coils and phases overlap one another as shown, the different phases being distinguished by heavy and broken lines respectively. The three phases are "Y" connected, the neutral connection "O" being shown at the bottom. If a little time is spent tracing the connections, the method of winding is easily grasped. Only one conductor per slot is shown, but in practice, especially with small high voltage machines, there may be between thirty and fifty conductors per slot. A complete induction motor with short circuited motor, and having the end plates and rotor removed, is shown in Fig. 130.

If the three-phase motor winding shown diagramatically (Fig. 128) has four poles instead of only two, as shown, and the slots increased pro rata, there will be 72 slots in the four pole machine. That is $6 \times 4 \times 3 = 72$ —*i.e.*, the product of six slots, four poles and three phases. Such a stamping would not be suitable for a two-phase machine, as we should have $\frac{72}{2 \times 4} = 9$ slots per pole and phase, and as half the slots are on either side of each pole, we could only use eight slots. Few motor makers use the same stampings for two and three-phase motors, and other stampings are gnerally standardised, such, for instance, as 48 slots for a two-phase machine, giving 6 slots per pole and phase, or 32 slots giving $\frac{32}{4 \times 2} = 4$ slots per pole and phase.

Fig. 130 gives a good idea of the stator winding of a two-phase Johnson and Phillips motor. It has 96 stator slots, each pole having 6 slots. There are, of course, 16 poles, eight for each phase, so that the machine is an eight-pole motor, and will therefore have a light load (synchronous) speed of 750 revolutions per minute.

One of the first points which will be suggested to anyone on examining Figs. 128, 129, and 130 is that there will be

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a considerable leakage of magnetic induction across the mouth of the slots Such leakage occurs, as has been shown, from pole to pole of an alternator and across the mouth of the slots in the armature; the shorter the pole pitch, other things being equal, the greater the leakage. In the case of induction motors the stator poles may have

FIG. 130.—STATOR OF JOHNSON AND PHILLIPS' TWO-PHASE MOTOR WOUND FOR EIGHT POLES.

considerable pitch, but there is no distinct air gap between them, hence it is not so difficult for leakage to take place.

This leakage is termed peripheral dispersion, and was, along with the whole question of leakage in induction motors, fully discussed in a paper by Dr. H. B. Eschen-

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berg before the Institution of Electrical Engineers.* This leakage is not nearly so great as might appear likely, and in point of fact must be low if the motor is to have a high power factor. In addition to this peripheral dispersion, there is a flux which exists outside the iron core due to the sides of each coil, which are, as will be seen from Fig. 129, outside the actual core. This is frequently termed flank dispersion, and has been so described by Dr. Hans Eschenberg.

The peripheral dispersion is proportional to the length of the air gap, and is also influenced by the shape of the slots, while it is inversely proportional to the pole pitch, the number of slots per pole pitch, and the width of the mouth of each slot. Owing to the small cross section of the iron at the top of completely closed slots, and to the fact that a comparatively small leakage will fully saturate these, and make their reluctance practically equal to air itself, the leakage with completely closed slots is not so great as would at first sight appear. The leakage co-efficient may be taken for partially closed slots as 1.12 for small induction motors to 1.04 for large machines, though it may be as low as 1.02 with the air gaps found in practice. These figures relate only to one member, *i.e.*, the rotor or the stator, and it is convenient to assume the leakage co-efficient as the same for either, so that the flux interlinked with the rotor conductors may be multiplied by 1.25 to 1.08 to find the total stator flux.

The speed of induction motors is determined by the number of stator poles and the periodicity; this is evident from Fig. 125, where it is apparent that the rate at which the magnetic field due to the stator rotates is proportional to the poles and periodicity. We thus have :—

$$\text{Pairs of poles in } \textit{each phase} = \frac{\text{cycles per second} \times 60}{\text{light load speed}} \quad .. \quad (13)$$

the pairs of poles being, of course, multiplied by two

* *Journal Institution of Electrical Engineers*, Vol. 33, page 239; also "The Induction Motor," by Behrend, *New York Electrical World and Engineer*; and Hobart in the *Elektrotechnische Zeitschrift*, Nov. 12, 1903, and in the *Electrical World and Engineer*, New York, April 30, 1904.

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to obtain the number of poles in each phase. For instance, the motor shown (Fig. 125) has four poles, but it has only two poles per phase, consequently on a 50 cycle circuit the rotor would run at 3,000 revolutions per minute, and in the case of four pole two and three-phase motors, though the total apparent poles—*i.e.*, poles multiplied by phases—would be eight and twelve respectively they are nevertheless four pole motors; hence their speed will be 1,500 revolutions on light load.

In order to keep down the peripheral leakage, it has been shown that a considerable pole pitch is desirable, this leakage determines the magnitude of the power factor, it is also apparent that in order to obtain slow speeds, the number of poles must be increased; we thus have two opposing considerations, and slow speed apparently can only be obtained, where the periodicity is fixed, by increasing the number of stator poles, which increases the leakage and lowers the power factor, or we must increase the diameter, making a more expensive machine with a longer pole pitch. H. M. Hobart has shown very clearly that the end connections—*i.e.*, the sides of the coil—lying outside the stator core* play a more important part in the production of leakage flux and increased inductance, than is generally supposed, the length of these are increased by an increase in the pole pitch, hence slow speed induction motors with satisfactory characteristics can only be obtained by reducing the frequency or by sacrificing some more important consideration, such as the power factor and the apparent efficiency as well as the overload capacity, and last, but not least, at an increase in price owing to the greater copper and iron necessary. It may, therefore, be taken for granted that were slow speeds generally necessary—*i.e.*, where the bulk of the industrial applications of motors were to very slow speed apparatus—the standardisation of modern polyphase design along a standard of 50 cycles would not have taken place. As

* "The Design of Induction Motors, with some European Examples." By H. M. Hobart, *Electrical World and Engineer*, New York, April 30, 1904.

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it is generally convenient, and almost always cheaper, to obtain slow speed by mechanical means rather than by the use of slow speed motors, the disadvantages due to 50 cycles in the few cases where very slow motors are wanted are so insignificant compared with the commercial advantages of being able to obtain 1,000 and 1,500 revolution motors, neither of which speeds are commercially practicable with 25 cycles, as to altogether overbalance the advantages which are derived from low periodicities. The influence of periodicity on speed must, however, be kept in view when designing large self-contained plants for pumping, certain classes of rolling mills, etc.

The dimensions of induction motors may be determined in the same manner as already described for generators, viz. :—

Watts per revolution $\times K_n = D^2 + L$ . . (14).

Where Km is a co-efficient depending upon the size and on the periodicity, D = diameter of the rotor and L the width of the rotor. Km has the values shown in table. These are deduced from current practice in two and three-phase motors.

TABLE XVII.

Periodicity.	Value of Km.
25 cycles	80—85
40 ,,	95—105
50 ,,	100—110
60 ,,	115—125
75 ,,	140—145

The watts are, of course, B.H.P. $\times$ 746, and are used for convenience in preference to any fraction of a horse power or foot pounds. The values given are fairly representative of modern practice, though several motors which the writer has measured up give lower values of "K_m," due to designers, owing to stress of competition, cutting the material down as far as possible. These co-efficients can be reduced in larger sizes, depending on the ventilation and the quality of the iron (core losses). At 100 horse power with effective ventilation these co-efficients can be reduced by 7 to 10 per cent., but

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beyond that power only a small reduction is possible if a temperature of 70 degrees F. is not to be exceeded. Knowing the product $D^2 \times L$, it is not difficult to get the correct size of the core taking angular velocities of 5,000 to 6,000 feet per minute for the rotor speed, though for small machines this angular velocity will not be found possible, 2,500 to 3,500 being nearer what is found in practice. This is owing to the small diameter of the rotor and the fact that the upper limit of the speed is set, not by economical surface velocities, but by the periodicity and number of poles, and is for 50 cycles 1,500 revolutions per minute.

The density of the magnetic induction has now to be fixed, and this is done by taking an air gap

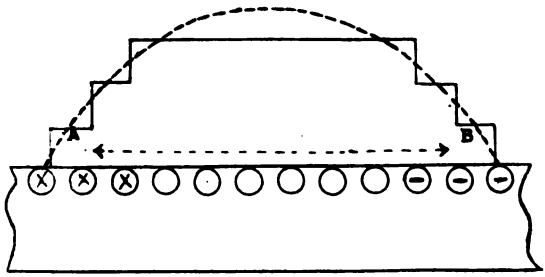

FIG. 131.

induction of about 18,000 lines per square inch and multiplying this by the average polar arc of one stator pole—*i.e.*, the average length of the inner periphery of one stator coil. If there are only two slots per pole and phase—*i.e.*, one slot on either side of the pole, as Fig. 125, the length of this inner periphery is easily determined, being the distance between the two sides of the coil. If there are several slots per pole and phase, as Fig. 128, the mean is taken which, in the case of a coil having six slots per pole and phase, is roughly the distance between the centre slots of one pole, the distance A B Fig. 131; this, multiplied by the length of the core parallel to the shaft, gives the polar area, which, if

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multiplied by the air gap induction already mentioned, results in the total flux per pole.

The reason for this will be apparent if we take Fig. 131 and consider it as one pole of one phase, having one turn per slot and six slots per pole. The total turns per pole will then be three as is obvious from the figure; suppose a current of 20 amperes passes through the coil the total ampere turns will be 60, and the ampere turns and therefore the magneto-motive force will be unequally distributed across the pole face; for instance the ampere turns due to the first turn occupying the outside slots will be 20, that due to the second turn occupying the middle slots will be the sum of the ampere turns due to itself and those outside it, *i.e.*, 40 in this case, while the ampere turns at the centre of the coil would be equal to the sum of all, or 60 ampere turns. The magneto-motive force, and, therefore, the magnetic induction,

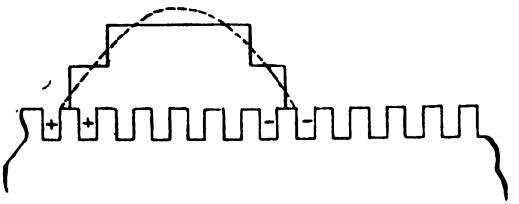

FIG. 132.

would be distributed in this manner, and in order to give a mental picture of the flux distribution in the stator winding, Fig. 131 has been drawn. The dotted line shown will indicate the approximate form of the wave of counter electromotive force in the stator winding; this is not nearly a sine wave, but with a shorter pole pitch (Fig. 132) it would be more nearly sinusoidal; the shorter the pole pitch, and also the smaller the slots per pole, the more peaky the wave, for we must think of the back E.M.F. as generated by a magnetic field passing round the stator at a speed proportional to the periodicity and the number of poles; hence if we consider the stator of an induction motor from this standpoint we see that all the laws

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which operate in the case of a generator are operative to the same degree in the case of an induction motor. To find the total stator conductors we merely use the formula (3) given for generators, and for convenience, instead of taking speed and the poles, we convert the formula as shown—

$$\text{E.M.F.} = \frac{K \times M \times Taw \times n \times P}{60 \times 2 \times 10^8} \quad . \quad . \quad . \quad (3)$$

where K is the coefficient, Fig. 12, Chapter V., M is the magnetic induction, Taw is turns of stator wire, n is revolutions per minute, and p poles, while the factors 60 and 2 reduce poles and revolutions to cycles per second. It is therefore apparent that the formula for generator E.M.F. (3) could be stated for a motor as

$$\text{E.M.F.} = \frac{K \times M \times Taw \times \text{cycles per second}}{10^8} \quad . \quad (15)$$

$$\therefore \quad Tsw = \frac{10^8 \times \text{E.M.F.}}{K \times M \times \text{cycles}} \quad . \quad . \quad . \quad (16)$$

where Tsw are, in this case, turns of stator wire, and E.M.F. the voltage per phase.* The stator turns are therefore those which, if interlinked with the magnetic induction already determined, at the periodicity of supply, will give a back E.M.F. equal to the impressed E.M.F., this back E.M.F. may be defined as the back E.M.F. of self-induction. The coefficient K which is given, Fig. 12, Chapter V., applies to induction motors. The ampere wires per inch of periphery may not greatly exceed the values shown, Fig. 133. The full load amperes per phase, and therefore in each conductor, can be found from the following formula, the derivation of which is obvious :—

$$\text{Amperes in each phase} = \frac{\text{B.H.P.} \times 746 \times \text{pf} \times \text{eff}}{\text{No. of phases} \times \text{Volts per phase}} \quad (17).$$

The section of the stator wire can now be fixed from this, and it may be from 900 to 1,500 amperes per square inch. Measurements on standard machines made by Brown, Boveri, Kolben and Co., Prague; Bergmann, Berlin; Westinghouse and B.T.H., England, point to about

* The voltage per phase has already been defined. See Chapter VI., pp. 54 and 55.

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1,000 amperes per square inch for 100 horse power, increasing as the machine gets smaller to 1,500 amperes per square inch at 2 horse power. Of course, other considerations influence this, such as permissible $C^2 \times R$ loss, so that these may be considered as approximate only.

The stator teeth should be proportioned to give a flux density of about 50,000 to 52,000 lines per square inch, and about 33,000 to 38,000 lines in the remainder of the iron; the slot depth is generally about three times the width. There is no such diversity of practice as

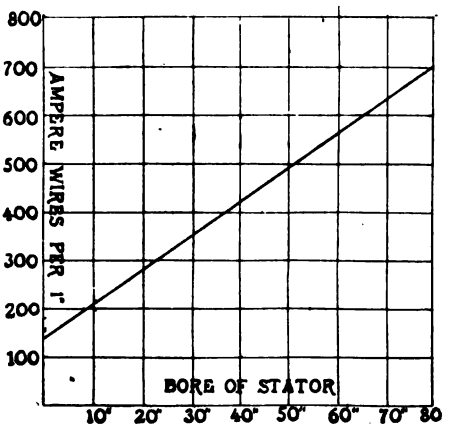

FIG. 133.

there is in the case of generators, rectangular slots of the shapes Nos. 2, 3, 4, and 7 (Fig. 20, Chapter VI.) being most common, the open slots, 2 and 3, being common in the United States and also the standard practice of the Electric Construction and Westinghouse Companies, though most other firms in Britain and on the Continent of Europe use closed or partially closed slots similar to Nos. 4 and 7.

A reduction of some importance can be effected in the linear dimensions of the machine, and therefore a saving in copper and iron can be effected by the use of

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specially high grade iron. Some Continental firms have devoted much attention to this, and at least one German firm, remarkable for the small size and, therefore, low cost of their motors, use a very high grade iron, which, though costing more, seems, by reason of the other economies resulting from its use, to enable them to keep within the limiting temperatures generally specified and yet supply small motors.

Having covered the principal considerations governing the design of the stator as far as we can without introducing the rotor, we will now turn to the secondary member. It has been explained how this derives its current from the stator, and one form of rotor has been illustrated, Figs. 127 and 129. The fundamental fact that the rotor must run slower than the stator if any E.M.F., and therefore current, is to be induced in it has doubtless been grasped, and the additional fact that the torque is proportional to the watt component of the rotor current and the magnetic induction linked with the rotor conductors must be accepted without proof in the meantime.

It will be apparent, on reflection, that as the rotor runs, say, 5 per cent. slower than the stator field, the variation of the rotor flux will only be 5 per cent, of the stator flux, *i.e.*, the active magnetic induction which becomes interlinked with the rotor winding will be small relative to that interlinked with the stator winding, and which produces a back E.M.F. in the stator. This will be apparent, because if, as already pointed out, when the speed of the two are equal, as is almost the case at light load, the magnetic lines cut by the rotor are smallest, and when the rotor is at rest the flux cut is a maximum—in the former case, perhaps, a fraction of 1 per cent., in the latter 100 per cent.—this brings us to a convenient method of measuring the E.M.F. induced in the rotor windings if we know the number of turns on the rotor, the slip, and the magnetic induction due to the stator.

The periodicity of the rotor current will obviously be governed by the same considerations; hence if the

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stator periodicity is 50 cycles, and the slip is 5 per cent., the rotor periodicity is $2\frac{1}{2}$ cycles per second. We thus have the following equations :—

Magnetic flux interlinked with rotor winding $= \frac{S_1 - S_2}{S_1} \times$ stator flux . (18)

and for the rotor periodicity,

cycles per second $= \frac{S_1 - S_2}{S_1} \times$ cycles of supply . (19)

where S_1 is speed of stator field, and S_2 speed of rotor. If the rotor magnetic flux were always as small as that apparently necessary from (18), the amount of rotor iron would be small, but, as has been seen, the magnetic induction through the rotor at rest is equal to the total flux less the leakage, which may reach 10 or even 20 per cent. in small machines, therefore it is necessary to proportion the rotor section so that this flux can be carried, as otherwise, owing to the great magnetic reluctance of an over-saturated rotor, the leakage would be abnormal, and the motor would be deficient in starting torque and overload capacity.

The rotor teeth are proportioned for a flux density about 5 to 10 per cent. greater than the stator teeth density, *i.e.*, 55,000 to 58,000 lines per square inch.

The next, and a most important point, is the number of rotor slots. There must never be the same number of stator and rotor slots, because, if so, there will be "dead points," which will probably prevent the starting of the motor against heavy loads and make the turning effort uneven when starting against smaller loads. It is general, therefore, to make the ratio,

$$\frac{\text{stator slots}}{\text{rotor slots}} = \frac{2}{3}, \frac{3}{4}, \frac{3}{5}, \frac{4}{5}, \frac{4}{6}, \frac{5}{6}, \frac{6}{8}, \frac{6}{10},$$

and so on.

The length of the air-gap is the next consideration, and its importance will be recognised when its influence on the power factor is taken into consideration. The amperes necessary to set up the magnetic field is, as has already been pointed out, wattless, and therefore the smaller this amount, the smaller the wattless component of the stator current. The air-gap is therefore

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reduced to that necessary for mechanical clearance, and is from .02 inch, with a rotor 6 inches, to about .135 inch at 50 inches. Kapp gives the figures as:

(D × .0025) + .008 = length of one air-gap (inches). (2)

where D is the diameter of the rotor.

The general characteristics and the value of the rotor current can now be determined by the means of what is known as the Heyland circle diagram. It is perhaps the most convenient and simple method of solving all induction motor problems. This is shown Fig. 134, there OE is the phase position of the impressed voltage, that is, the volts per phase. The current taken by the motor at light load consists of two parts: one, the current

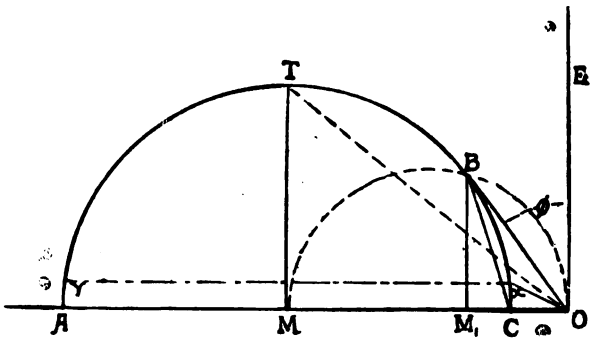

FIG. 134.

which, when multiplied by the volts, gives the watts required to overcome the hysteresis and eddy current loss, windage and bearing friction, and second, the current necessary to maintain the magnetic induction in the stator, rotor, and air-gap. The former being an energy current is in phase with the supply or impressed volts, and the latter the magnetising current which lags 90 degrees behind the impressed volts. The magnetising current is found from the ampere turns necessary to produce the required flux, the method of calculating it will be found from formula 7 (for the air-gap) and the curves Fig. 6. The ampere turns re-

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quired are divided by the turns of the stator winding, and the resultant amperes are laid off along the line OA from O to C; this is, of course, amperes to any convenient scale.

The most important thing is now to settle the ratio of the total stator flux to total leakage flux, *i.e.*, leakage from rotor and stator, as upon this ratio depends the overload capacity and maximum torque of the motor. This ratio, which is denoted for convenience by x, is

$$= \frac{1}{J_1 \times J_2 - 1} = x \quad . \quad . \quad (21)$$

where J_1 is stator leakage coefficient, and J_2 rotor coefficient. Now multiply the magnetising current OC

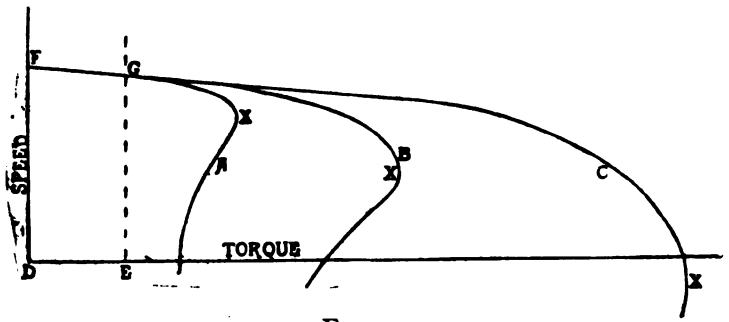

FIG. 135.

by x, which gives the length of the line CA. It will now be clear that CA will be longer the smaller the leakage coefficients, and the greater the magnetising current OC; but that small leakage exercises a preponderating influence; for instance, a change in the leakage coefficients of rotor and stator from 1.1 to 1.05 would greatly increase the length of the line CA.

The great importance of a small magnetic leakage and its influence on the maximum torque of the motor is clearly shown in Fig. 135, where the speed and torque are plotted with torque as abscissæ and speed as ordinates, F being no-load speed of the motor, and G. full-load speed, the dotted line EG being full-load torque.

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If the curve A is taken as the speed torque curve with a certain magnetic leakage B will be the speed torque curve with half the previous leakage, and C will be the same curve if the leakage is reduced to one-fourth. It will be seen that notwithstanding the fact that the drop of speed between no load and full load, F to G, is the same in each case, yet one motor, curve A, has a maximum torque, denoted by X, *i.e.*, overload capacity before falling out of step, of only about 100 per cent., while curve B denotes a motor having an overload capacity of 250 per cent., the maximum torque of curve "A" occurring at X, about 25 per cent. drop in speed, curve "B" at 50 per cent., and in the case of the motor curve "C," at standstill.

To return to Fig. 134, draw a semi-circle joining C and A, the maximum height, MT, of this semi-circle being proportional to the maximum torque of the motor. To make further use of the diagram it is necessary to make the assumption that the leakage does not vary with the load, nor does the permeability of the motor iron. Then a line from O to any point on the semi-circle, say B, will represent stator amperes per phase to the same scale as OC, and if a line is drawn from B to C, we have a figure which is in some measure proportional to the rotor current. To find the actual rotor current per bar we take the values as follows :—

$$BC \times \left(J_2 \times \frac{\text{Total stator turns}}{\text{Total rotor bars}^*}\right) = \frac{\text{rotor current}}{\text{per bar}} \quad . \quad (21)$$

where stator and rotor turns are turns in series on each phase. A vertical line drawn from B to M_1 on the base is proportional to the torque of the motor at that particular stator current, similarly the dotted line OT and the heavy line TM represent stator current, and the torque at that current.

A point on the circle ATBC may be determined on the test plate; it lies between A and T, and a line from O to this point, which we will call V, represents the current taken by the machine when the rotor is locked.

* In small motors with wound rotor this may read rotor turns, as it will probably be wire-wound.

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It is usually termed the short circuit current, and may be 3 to 5 times the length of O.B., though much depends upon the design. It has a lower power factor as will be apparent, as the angle ϕ would be greater.

The angle OB, OE, or, for maximum torque, OT, OE, is the angle of lag of stator amperes behind stator EMF, the cosine of which is the power factor of the motor; the power factor will therefore be a maximum when the line BO is at a tangent to the semi-circle. That the vertical lines, such as TM, BM, and any others that one may draw, are proportional to the torque, and therefore the output at a given speed of the motor, will be apparent when one considers that the output of the motor is proportional to the watt component of the input, *i.e.*, true watts input, and if the lines OB, OT, represent the total amperes, TM and BM must represent the watt component of this current. One correction should be made. Draw the line Ox equal to the current of the motor on no-load, then Cx represents the watt current to overcome bearing friction, iron losses, and windage, and must be subtracted from the length of the lines BM and TM; in other words, measure the torque from the broken line XY. This leaves out of account the copper loss, which, however, is not a large proportion of the total losses in modern induction motors.

The actual torque must be determined by making a scale for this purpose, as while the lines BM and TM may be proportional to the torque, they cannot be considered as a measure, because all the lines have been laid off to a scale of amperes, and this scale cannot, of course, be used to measure a totally different value; the torque is

$$\frac{\text{H.P.} \times 3300}{2\pi \times \text{revs.}} = \text{pound feet} \quad . \quad . \quad . \quad (22)$$

$$\text{or} \quad \frac{\frac{\text{watts}}{746} \times 33000}{2\pi \times \text{revs.}} = \text{pound feet}$$

reduced to its lowest terms; this becomes:—

$$\text{pound feet} = \frac{\text{watts} \times 44.4}{2\pi \times \text{revs.}} = \frac{\text{watts}}{\text{revs.}} \times 7.06 \quad . \quad . \quad (23)$$

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It is convenient to remember, apart from the rapidity of the process, that the *watts per revolution* multiplied by seven gives the torque in pound feet.

The total losses in the motor can now be determined, the iron losses in both stator and rotor may be determined from Fig. 9, but the rotor iron loss is not sufficiently great to be taken into account owing to the low periodicity,* and the losses due to $C^2 \times R$ may be figured, taking the total current, not the watt component only, the rotor copper loss may be figured as directly proportional to the slip, the sum of these losses gives the total internal loss in the machine, and the temperature may be figured as about 70° F. with 1 watt loss radiated per square inch of exposed surface. With the open stator frame used in modern induction motors the surface of the stator core may be reckoned as effective radiating surface, but this varies within wide limits as the core ventilation plays a most important part in determining the temperature and output from a given carcase.

It should be noted in passing that the rotor E.M.F. does not influence the machine except inasmuch as it is dependent upon the number of rotor bars and the flux interlinked with them, which is of course proportional to the slip. It is unnecessary to calculate this rotor E.M.F. and designers seldom do so. If the E.M.F. required to drive the rotor amperes through the winding is considerable owing to the high resistance, then the slip will be greater in proportion to the drop in E.M.F. through the rotor winding ; thus the slip from no-load to full-load is a measure of the amount of rotor copper, just as the difference in speed between no-load and full-load is to some extent a measure of the drop in pressure through the armature winding, and therefore indicative of the amount of armature copper in a direct current motor.

Induction motors having considerable drop in speed

* It has, however, been shown by Hissink and others in the German technical papers that there are hysteresis losses in the rotor teeth due to variations in the magnetic induction as the rotor teeth pass the stator slots or teeth.

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between no-load and full-load have therefore large $C^2 \times R$ rotor drop, and consequently only a small amount of rotor copper.

The slip and overload capacity usually found in induction motors is about that shown in table.—

TABLE XVIII.

H.P.	Slip.	Overload capacity.
¼	7½ %	80 % increase.
2	3½ %	100 % ,,
5	3 %	125 % ,,
15	2½ %	150 % ,,
30	2 %	200 % ,,
100	2 %	250 % ,,

We have now covered the general principles underlying the design of the induction motor, and the reader will have grasped the influence of the stator and rotor winding, and the important part which leakage plays in the performance of the machine. The characteristics of the two most common types of induction motor, viz., those with short-circuited and those with wound rotor, will now be dealt with. It has doubtless been the impression that the induction motor with short circuited rotor, as illustrated Figs. 127 and 129, possesses so many advantages, both from a mechanical and electrical standpoint, that its superiority is unquestioned. If the induction motor with short-circuited rotor only had to start against very small load, its defects would not be apparent, but as most motors have to start against a load of greater or less magnitude the grave defects of this type of motor come to the surface. When switched on to the circuit with the rotor at rest the total flux cutting the rotor bars is, for the moment, a maximum, and as these bars have very low resistance the resultant current is enormous; the effect of this large rotor current is to react upon the stator and oppose that part of the stator flux passing through the rotor, thus causing the flux to pass from pole to pole across the face of the stator, *i.e.*, increasing the peripheral leakage, the stator current being scarcely reduced at all because of the enormous rotor currents cancelling the self induction

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of the stator winding, and thus permitting the large stator current to pass. The torque is comparatively small, because it is proportional to the flux interlinked with the rotor bars, which we have seen is small owing to the leakage, and to the watt component of the rotor current. Moreover, as has already been pointed out, the leakage flux determines to a large extent the power factor of the

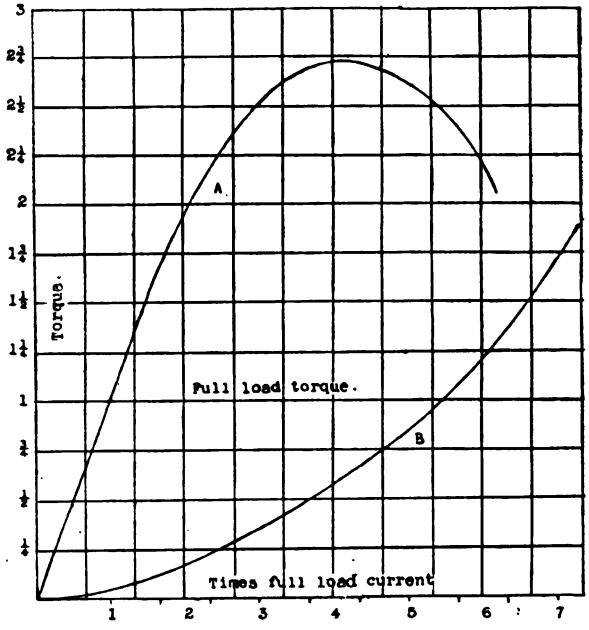

FIG. 136.

motor, and this is now considerable, hence the power factor of the stator current is small, and its influence upon the pressure regulation of the supply system is consequently bad.

Some idea of the starting current of a three-phase induction motor with short-circuited rotor will be gathered from Fig. 136, curve B of which shows the

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starting torque with varying stator current. It will be seen that if the motor is to start with not more than full-load amperes, it will not exert more than about one-tenth of its full-load torque; even at half full-load torque it takes about three and a half times full-load amperes, while if full-load torque is wanted, about four to five times full-load amperes, depending upon the design, will be necessary. This curve was plotted from a series of experiments with a 10 horse-power three-phase motor, and may be taken as approximately characteristic of the performance of polyphase motors with short-circuited rotors. Curve A, on the other hand, shows the approximate starting current for a given starting torque of an induction motor with a wound rotor, having a secondary resistance of suitable value in series

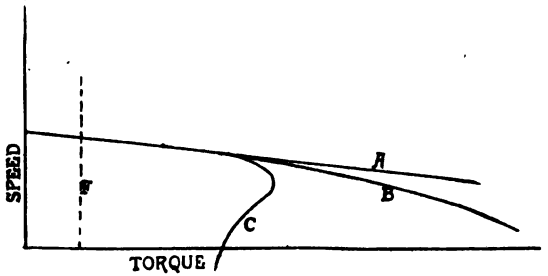

FIG. 137.

with the rotor winding. It will be evident, therefore, that if a reasonable starting torque is wanted, a machine with a wound rotor is a necessity. As will be shown later, an auto-transformer, or starting compensator, does not seriously reduce the current taken from the line. What a compensator really does is to transform the energy which would otherwise be lost due to $C^2 \times R$ in the resistance which is in series with the stator winding, into useful energy, but it exerts no other influence, and is therefore only useful for moderate starting torque. This will be dealt with later. The motor is therefore apparently unsuited for starting against heavy loads, unless

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some modifications are introduced ; this is what has been done, for while the motor starts perfectly well on a loose pulley, numerous modifications have been introduced to make it start under other conditions.

To fully grasp the characteristics of the induction motor and the influence of resistance in the stator or in series with it at speeds between zero and synchronous (maximum possible) speed, that is, between starting and full speeds, the diagram Fig. 137 is given. Here the torque is plotted as abscissæ and speed as ordinates. Curve A represents the torque speed curve, did the stator winding of the motor have no resistance ; from which it will be apparent that were this the case the torque of an induction motor would be inversely proportional to the speed. The effect of the resistance of the stator winding is that with the heavy currents necessary for the large torque the drop of pressure due to C × R lowers the actual E.M.F. effective for sending current through the stator winding, hence the stator current, and therefore torque, does not grow in strict proportion to any reduction in speed, which corresponds, or should correspond in an ideal motor * to an increase in torque ; thus the addition of stator copper drop causes the curve A to bend down with heavy currents (torque)† till it is of the shape B.

Magnetic leakage, as has been shown, plays a most important part in determining the maximum torque of the machine, and in this case it distorts the curve still more till it becomes of the shape shown, " C," where the maximum torque occurs at about ¾-full speed, *i.e.*, with a slip of 25 per cent.; this may for the moment be considered as the actual speed torque curve of an induction motor, while the curves A and B represent the performance of the same motor under the unattainable conditions already defined. From the shape of curve

* By ideal motor is meant a machine having neither stator copper resistance nor magnetic leakage.

† It is obvious that great torque is inseparable from equally great current ; hence the abscissæ might be plotted on stator amperes instead of torque.

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" C " it will be readiiy understood why, when a motor is loaded beyond the maximum possible torque, it drops out of step and stops.

To take the first of the suggestions, viz., a high resistance rotor, it is at once apparent that winding the rotor with material of higher resistance than copper will enable us to keep down the rotor current ; this, however, will increase the slip at full speed, as the slip is proportional to the $C^2 \times R$ losses in the rotor and, moreover, will also increase the temperature, so that unless the machine is well ventilated, and other methods of starting are objectionable, this is not desirable. Motors con-

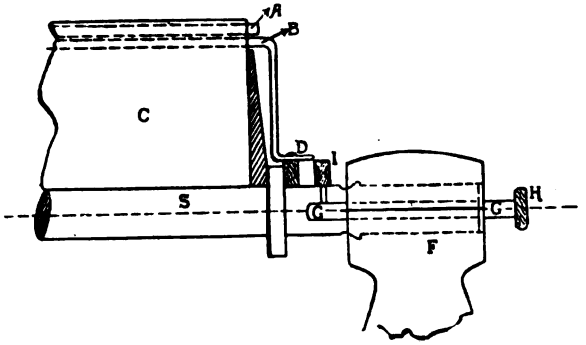

Fig. 138.

structed in this way are, however, employed for intermittent work, such as driving centrifugal machines and crab motors on cranes. Another way is to construct the machine with two rotor windings, one of high resistance and another of low resistance, the former being employed at starting, the latter being switched in when nearly full speed has been reached. This method is convenient and cheap where a moderate torque is necessary. Fig. 138 shows the general arrangement. C is the rotor core mounted on the shaft S carried by the bearing F. A and B are the two windings occupying the same slots, the ends of B being brought down to the contact D.

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Assuming that A is the high resistance winding which is permanently short-circuited, the handle H, operating the contact I through the rod G (which passes through the shaft) is pulled out, leaving the low resistance winding open. The stator field thus induces current only in the high resistance winding. As soon as the speed has become sufficiently great the handle H is pushed in, which causes the contact ring I to make contact at D, thus closing the circuit of the low resistance winding. The fact that the high resistance winding A is permanently closed is not a serious matter, as the current induced in it at full speed would be a very small amount relative to that in the low resistance winding; hence the $C^2 \times R$. loss would be small; in fact, it is almost negligible.

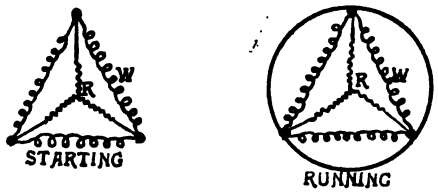

FIG. 139.

This method of having a greater rotor resistance at starting has also been arranged with a plain low resistance delta connected winding and a number of resistance coils inside the annular space of the rotor spider on which the core is mounted, these resistances being short-circuited by the movement of a handle similar to that used for a motor with two rotor windings. This is shown diagramatically, Fig. 139, where R is the resistance and W the rotor winding, the short-circuiting ring being seen in the running position.

Messrs. Siemens and Halske have a method which is an ingenious modification of this. Fig. 140 shows diagramatically a "Y"-connected rotor winding, each leg being in two parts, one having approximately twice the number of turns of the other; the E.M.F. induced in

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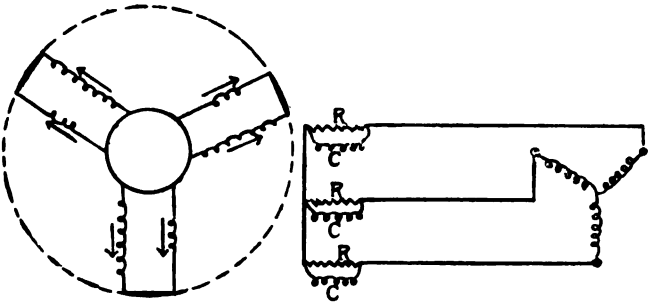
one winding is therefore twice that of the other, and with the two in opposition the volts available to send a current through the winding will be the difference between the two E.M.F's. As soon as the motor gets up to speed the ends are short-circuited by the ring shown dotted.

Another ingenious starter which, unlike those already described, is automatic, consists of a machine having a " Y "-wound rotor and slip rings, connected to two non-inductive resistances R Fig. 141, the latter being short-circuited by choking coils C, which, of course, have low ohmic resistance, but large self-induction. As the periodicity of the rotor current is high



FIGS. 140 AND 141.

at starting, the choking coil will offer considerable opposition to the passage of the current; hence most of it will pass through the non-inductive resistances. As the machine gains in speed the frequency of the rotor currents decreases, and the back E.M.F. of the choking coil will likewise fall. More current will then pass through the choking coil and little, if any, through the resistance. It will be seen that this is performed automatically, depending upon the periodicity of the rotor current, which is in turn fixed by the slip. This method was patented in Hungary by Fischer Hinnen, and an interesting modification has been designed by Mr. A. P. Zani, chief designer to Messrs. Dick

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Kerr, the principal difference being that Mr. Zani has provided the choking coils C, which, by the way are fixed inside the spider of the rotor, with movable cores, so that as the speed grows the centrifugal action tends to cause the cores to move outward, and by increasing the magnetic reluctance of the circuit, and therefore decreasing the self-induction even below the very low value which it has, because of the low periodicity, practically provides an alternative path of low ohmic resistance and negligible self-induction.

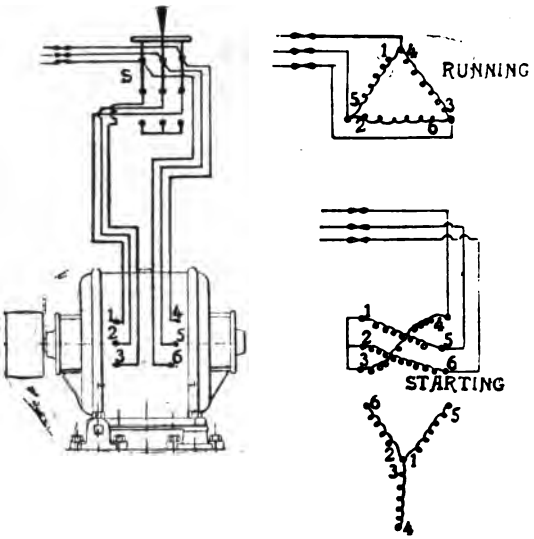

FIG. 142.

Another method of starting a motor having a short-circuited rotor without the use of an external resistance is known as the "star to delta" method, where the motor is wound with a delta connected stator, which is, at starting, arranged for star connection. To secure this the motor windings are brought to six terminals of the stator, as shown Fig. 142, and a change-over switch

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is connected as shown. The actual stator connections are shown alongside the motor, where the diagram is numbered to represent the terminals as they are grouped on the outside of the frame. At starting the connections are as shown, but with the change-over switch "S" on the *bottom*, when the stator winding is star-connected, and the current per phase will be reduced in proportion to the ratio of the back E.M.F. under the two conditions, so that if wound for a given line voltage under normal running condition (delta connection), the motor winding will present $\sqrt{3}$ times the impedance to the passage of the current, as the turns producing a back E.M.F. are obviously increased in this proportion, hence the current taken when the motor is switched directly on to the mains is, instead of, say, three times the full-load amperes, only about 1.73 times full-load amperes with a considerable reduction in torque; hence the machine will take longer to accelerate with the smaller current, unless the load is small, but the end has been achieved, viz., the reduction of the starting current. When considerable speed has been reached the change-over switch is turned over to the top contacts, when the motor is connected delta, and runs in the usual way.

This proceeding is sometimes reversed when greater starting torque is wanted, and the amount of current taken is immaterial. Messrs. Brown Boveri and Co., of Baden, Switzerland, have on several of the mountain railways equipped by them arranged the motors, which are wound for star connection, so that they are switched on delta-connected; the current taken is then $\sqrt{3}$ times greater than that corresponding to the star connection, and the torque correspondingly increased, as will be seen from Fig. 136.

The most obvious method of keeping down the starting current is by means of an ordinary resistance in series with the stator winding, but as this also reduces the torque in proportion to the square of the reduction in voltage, it is only useful in the case of motors starting against small loads as a means of limiting the initial rush of current when the motor is switched on.

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FIG. 143.—AUTO-TRANSFORMER.

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The next and one of the most usual methods is the use of an auto-transformer. This has been shown diagrammatically, Fig. 107, when dealing with the starting of synchronous motors, and need not be repeated, but an illustration of an auto-transformer, as made by the Westinghouse Co., is shown Fig. 143. The change-over switch by means of which the motor is thrown on to either the reduced voltage or the full voltage is shown on the top of the case. An auto-transformer is no advantage, except when it is desired to start the motor at some fraction of its maximum torque, as there must be, for any given torque, an E.M.F. sufficient to send the necessary current through the stator winding.

Most modern induction motors can with full voltage across the terminals take about seven times full-load current if the rotor is at rest, and the static torque with this current will be approximately twice full-load torque. Any reduction in the terminal volts will, as already noted, reduce the starting torque in proportion to the square of the reduction in pressure; hence with about 70 per cent. of full voltage the motor will give approximately full-load starting torque, and take about five times full-load current at starting. If the pressure is reduced by a resistance in series with the stator winding, as already described, the current taken from the line will be five times full-load amperes, the current passing through the resistance causing the line volts to drop to, say, 70 per cent. of its original value, and this lower pressure is available at the terminals of the motor to send the current through the windings. If, however, an auto-transformer is employed this effects a reduction in pressure, not due to back E.M.F. like a choking coil, but due to its transformer-like action; it is, in fact, just like the economy coil common in alternate current arc lighting; its action is shown diagrammatically in Fig. 144, where it is arranged to supply a motor with one-third of the line volts, and about three times full-load current, in which case the motor would give nearly half full-load torque. It is apparent, therefore, that the auto-trans-

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former in no way influences the starting performance of the motor, and its only effect is to save the energy which would be lost in the resistance were the pressure reduced by a resistance in series with the stator winding.

By using an auto-transformer instead of a resistance, the current taken from the line is therefore slightly reduced, but it still is considerable if a fair starting torque is wanted. In the case of a motor supplied with 70 per cent. of full voltage, and taking about five times full-load current, it would take from the line (supply system) about four times full-load amperes at full-line pressure. Instead of wasting energy in heating the resistance coils, it transforms the otherwise waste energy into useful energy at the lower pressure, there being, of course, small losses due to copper and iron. Table XIX. gives the results of a test on a 20 horse-power two-phase motor, giving varying starting torque with different voltages and currents.

TABLE XIX.—20 H.P. TWO-PHASE MOTOR STARTED THROUGH AUTO-TRANSFORMER, AT VARYING STARTING TORQUE.

Line Volts.	Line amperes per phase.	Volts at motor terminals.	Amperes supplied to motor.	Starting torque 1 = full load torque.	Remarks.
200	336	200	336	2	Motor at rest on full line volts.
200	245	160	275	1.28	Through auto-transformer.
200	190	142	240	1.0	,,
200	155	120	230	.72	,,
200	91	100	168	.5	,,
200	47	64	132	.32	,,
200	10.4	40	48	.08	,,

The full-load working current is 48 amperes per phase.

NOTE.—If no auto-transformer is used the current taken from the line would be that shown in the fourth column.

It will be seen that if the motor must not take more than full-load current from the mains it will, if started through an auto-transformer, only give 32 per cent.

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of its full-load torque, while if there was no auto-transformer, but simply a resistance, and the current taken from the supply limited as before to full-load amperes, the motor would develop less than one-tenth of its full-load torque.

It is usual to provide the auto-transformer with several tappings giving various secondary voltages, so that the most suitable may be connected to the motor side of the switch.

This practically exhausts the list of methods adopted to induce the induction motor with a more or less simple winding on the rotor to start with a reasonable torque without taking too much current from the supply mains. The inherent defect is, as will be seen, the fact that there

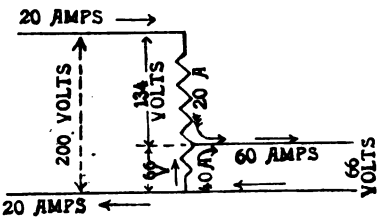

FIG. 144.—DIAGRAM SHOWING ACTION OF AUTO-TRANSFORMER.

is no way of limiting the enormous currents of relatively low power factor which are induced in the low resistance bars of the rotor, which, by cancelling the self-induction of the stator, permits considerable current to be drawn from the mains; except by increasing their resistance, the increase of rotor resistance is, however, prejudicial to the motor efficiency at full speed. The one practical alternative is to entirely remove this short-circuited rotor and replace it with a rotor having a winding connected to slip rings, and through brushes to an external non-inductive resistance which can be cut out as the motor comes up to speed. This is shown, Fig. 145, where the rotor winding is connected to the slip

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rings S, and through brushes pressing on them, to the non-inductive resistance RE. (the figures will be referred to later), which is generally arranged to reduce the rotor current to rather less than its full-load value, so that the stator takes less than full-load amperes when switched in, this current being gradually raised as the resistance is cut out. It will be seen that the greater the torque required the smaller should be the *wattless* component of the rotor current. This is determined by the self-induction of the rotor circuit, which is in turn

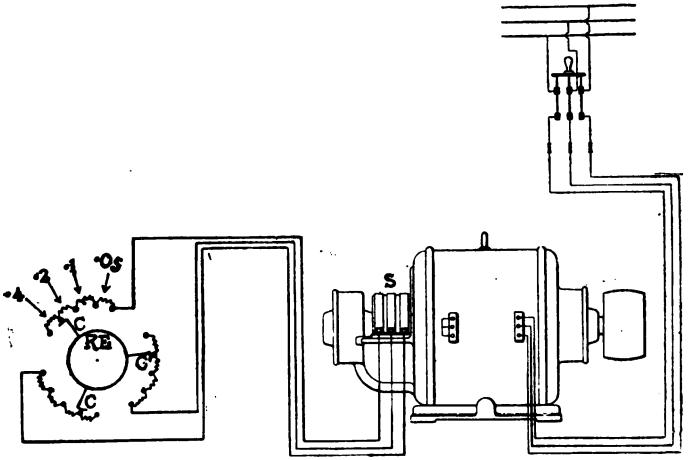

FIG. 145.

fixed by the amount of iron in the rotor (its inductance), the periodicity of the rotor current, and the current flowing in the rotor winding. The greater the rotor current, therefore, other things remaining equal, the greater the wattless component and the smaller the torque per ampere of rotor current.

Owing to the fact that at the instant of starting the rotor is at rest the slip is 100 per cent., and therefore, as already shown (formula 19), the periodicity is practically the same as that of the

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supply system; this cannot be reduced until the rotor has been speeded up. The only one of all these factors which influence the power factor of the rotor current that can be reduced when starting, is the rotor current which, by the insertion of a non-inductive resistance in series with the rotor winding not only diminishes the rotor current, and, therefore reduces the magnetic leakage by reducing the rotor reaction, but reducing the rotor current also reduces the inductance of the circuit, and so improves the otherwise low power factor of the current in the rotor windings.

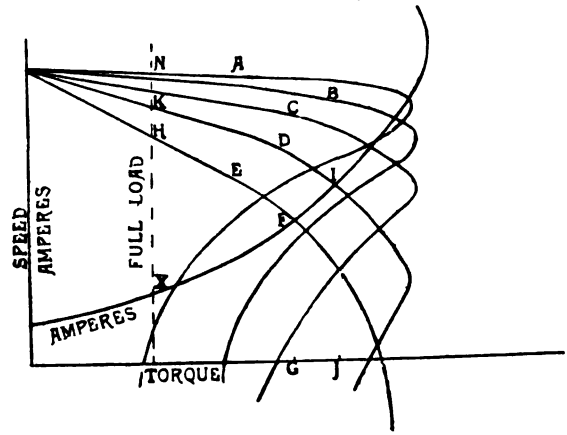

Fig. 146.

The actual influence of the rotor resistance on the torque and speed of an induction motor, and its performance with varying rotor resistance, will be more accurately followed from the diagram Fig. 146. The curves have been plotted from a motor having a wound rotor and different values of resistance inserted in series with the rotor winding, as shown Fig. 145, where the value of the resistance in one limb only is given, but the others are the same, the stator being on the full line voltage. The current curve is plotted, and is of course the same as already shown for a machine with a short-circuited rotor;

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the torque increases with the current till a certain maximum torque is reached, when, with any increase in current, there is a decrease in torque, hence a machine with a wound rotor does not have any different characteristics so far as this point is concerned. But the maximum torque for a given slip is very different. Curve A is the speed torque curve with the secondary winding short-circuited at the slip rings, B is with the total secondary resistance doubled, *i.e.*, a resistance of .05 ohms added to the secondary resistance. C is the speed torque curve, with the external resistance again doubled, or with .1 ohm in the external resistance. D and E are curves with secondary resistance of .2 and .4 ohms respectively. In each case it will be noted the doubling of the secondary resistance doubles the slip, which is as it ought to be, because the slip is proportioned to the energy wasted in the secondary; hence it is apparent that regulation by introducing resistance in the secondary circuit is no more economical than regulating the speed of a direct current shunt motor by inserting resistance in series with the armature.

Assume that the external resistance is arranged as Fig. 145, where there are four steps in the secondary external resistance, each of the value shown, then, as the motor is switched into the circuit, starting against full-load torque we should have the current F corresponding to the torque G, and the motor would accelerate till the speed rises to H, where it would remain constant; meanwhile the stator current would have fallen to X. Move the resistance regulator to the next step corresponding to a total resistance .2 ohm in the rheostat; the amperes will rise to a value equal to I, with a corresponding increase in torque as read on the abscissæ at J; this increase in torque would cause the rotor to rapidly speed up to the speed corresponding to K, and the current would fall back to X. This process is continued till the last movement of the rheostat short circuits the brushes causing the machine to accelerate to its normal full speed N. We thus have a speed current curve resembling Fig. 147, in which the current varies

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as section after section of the resistance is cut out, and the motor speeds up from zero to full speed against full load torque.

It will be obvious that if the motor is already at full speed, and the rotor resistance is increased by manipula-

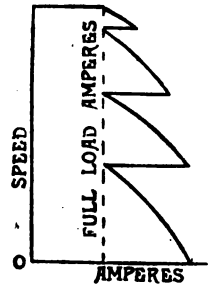

Fig. 147.

tion of the regulator, then the speed can be reduced, and it only wants a sufficiently large number of steps properly graded to effect a gradual change of speed from full speed to a few revolutions per minute, the output being in all cases proportional to the speed, the balance of the power being dissipated as heat in the regulating rheostat.

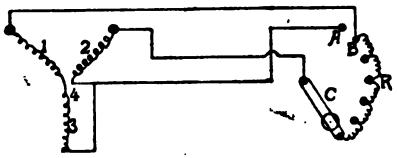

Fig. 148—Dr. Neithammer's arrangement of Starting Resistance.

An interesting modification of the rheostat shown, Fig. 145, is due to Dr. Neithammer, who cheapens the cost and reduces the number of contacts in the switch by putting all three phases in series with each other, and with a resistance. Fig. 148 shows how this is

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effected. The rotor has four slip rings and brushes, connected to phases 1, 2, and 3, and also to point 4. At starting the lever is placed as shown in the diagram, so that the current passes in series through all the phases and the resistance. On cutting out the resistance the lever C reaches the point B, where it covers the studs B and A, so that in the running position it is practically

FIG. 149.—ARRANGEMENT OF BRUSH LIFTING AND SHORT CIRCUITING GEAR ON LAHMEYER MOTOR.

a machine with a short circuited rotor. The motor in running position has a little more slip than a normal three-phase motor with short circuited slip rings, due to the smaller amount of current in phases 1 and 3, which necessitates greater slip for a given torque.

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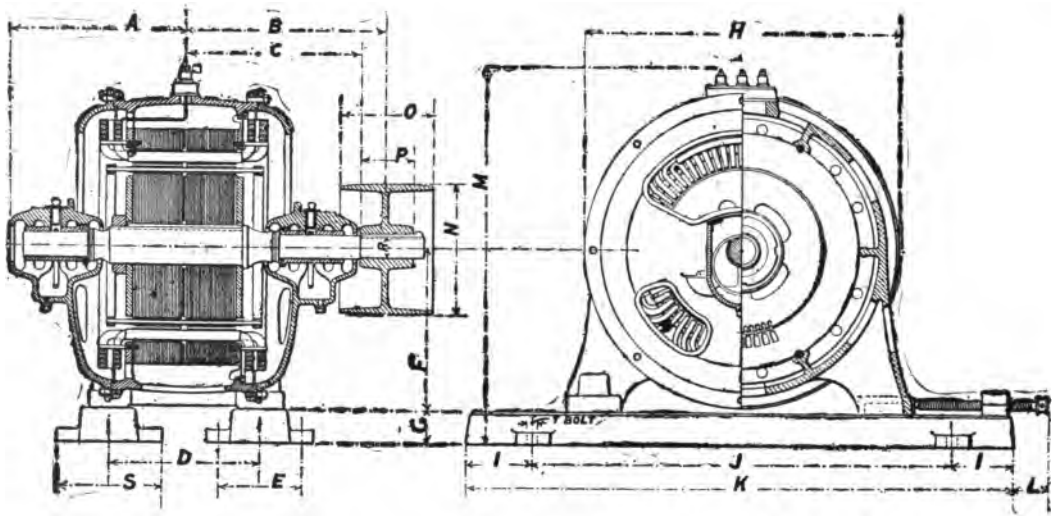

FIG. 150.—SECTION AND ELEVATION OF BRUSH COMPANY'S INDUCTION MOTOR WITH SHORT-CIRCUITED ROTOR.

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The rotor winding may be two-phase, three-phase, four-phase, six-phase, or, indeed, any number of phases, in fact, the greater the number of rotor circuits the better the power factor and overload capacity, due to the fact that the local E.M.F's due to leakage are reduced, though not nearly in proportion to the number of phases; three-phases are general, as the improved performance is so slight with any increase over that number, that it is not worth the extra complication and the additional cost of slip rings.

With nearly all constant speed motors having wound rotors, an arrangement is made for short circuiting the slip rings and raising the brushes; this adds about seven to 10 per cent. to the cost of the motor, but is a good investment where power is fairly costly, and the motor runs for long periods at or near full load. The lifting of the brushes and short circuiting the rings is usually effected by pushing a knob on the end of the shaft, or by a handle projecting up from the slip rings. One such arrangement on a Lahmeyer machine is shown Fig. 149.

The general features and characteristics of the induction motor have now been dealt with, and it remains to consider the construction of the machine. Fig. 150 is a section of a small Brush induction motor. The machine has a short-circuited rotor. Table XX. gives details of a somewhat similar motor of 2 horse-power, the speed being 1,500 revolutions per minute at light load, falling to 1,430 revolutions at full load, the efficiency and power factor being 85 per cent. and .88 respectively. Full details of this machine are given in table on following page.

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TABLE XX.—2 HORSE-POWER TWO-PHASE 50 CYCLE INDUCTION MOTOR, WITH SHORT-CIRCUITED ROTOR.

B.H.P.	2
Volts per phase	200
Revolutions full load	1,430
Revolutions light load	1,500
Slip at full load	4½ per cent.
Efficiency at full load	85 per cent.
Power factor at full load	.88
Stator slots	32
Area of stator wire	.0033 square inch
Amperes per phase	4.95
Current density in stator winding	1500 amps. per sq. in.
Turns per stator slot	35
Bore of stator	5.99 inches
Width of ,,	3.14 ,,
Weight of stator lamin. tions	68.5 lbs.
,, ,, ,, copper	12½ ,,
Diameter of rotor	5.94 inches
Width ,, ,,	2.87 ,,
Rotor slots	38 ,,
Area of rotor bars	.0258 ,,
Amperes per rotor bar at rull oad	32.5
Current density in rotor bars	1250 amps. per sq. in.
Maximum load before falling out of step	3.75 h.p.
Watts per revolution	1.05
Output co-efficient	90
Weight of machine complete	175 lbs.

The letails have been tabulated pretty fully in the foregoing to show the general features of these small induction motors,

The general performance of a 2 and 5 horse-power three-phase with short-circuited rotor motor is given—Figs. 151 and 152.

Table XXI. gives the leading features of a 25 and a 75 h.p. three-phase motor.

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TABLE XXI.—50-CYCLES, 3-PHASE MOTORS, WITH "Y" CONNECTED STATOR.

B.H.P.	25	75
Volts per phase	220	220
Revs. full load	965	735
,, light ,,	1000	750
Slip at full load	3½ per cent.	2½ per c.
Efficiency at full load	89½ ,, ,,	93.25 ,,
Power factor at full load	.85	.91
Stator slots	54	72
Amperes per phase	36 amps.	102 amps.
Current density in stator winding	1350 amps. per sq. in.	1200 amps. per sq. in.
Bore of stator inches	12½	20.12
Width of ,, ,,	8	11.03
Weight of stampings in stator	200 lbs.	600 lbs.
,, ,, ,, copper in stator	108 ,,	260 ,,
Diameter of rotor inches	12.45	20
Width of ,, ,,	7.8	11
Weight of stampings in rotor	115 lbs.	1195 lbs.
Weight of copper in rotor	70 lbs.	145 lbs.
Maximum load before falling out of step	50 h.p.	170
Watts per revol.	19.4	76
Output co-efficient	65	57
Weight of machine	1500 lbs.	3400 lbs.

The last example will be the details of a 500 horse-power three-phase induction motor of the slow speed type. This machine is used for driving a mining pump, and is mounted direct on the pump shaft. Such motors are common in Belgium and Germany not only for pumping, when they are built to run at speeds varying from 60 to 150 revolutions per minute, but also for winding purposes.

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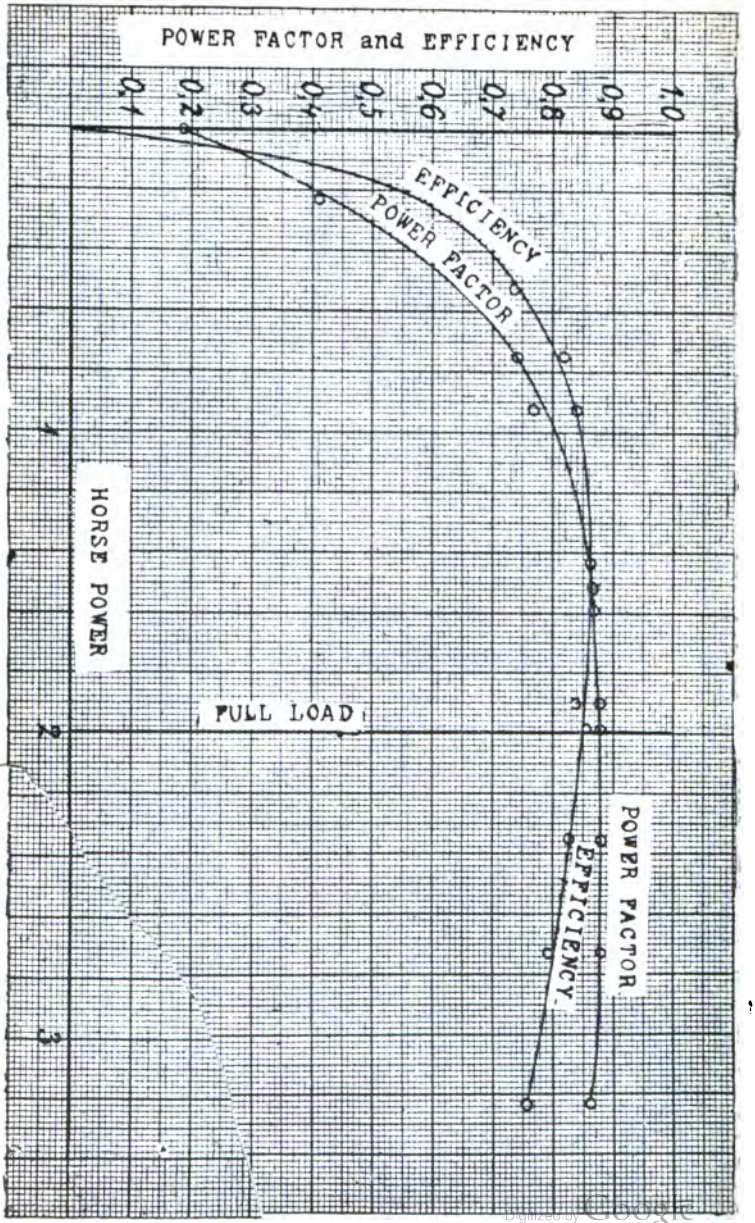

FIG. 151.—PERFORMANCE OF 2 H.P. INDUCTION MOTOR.

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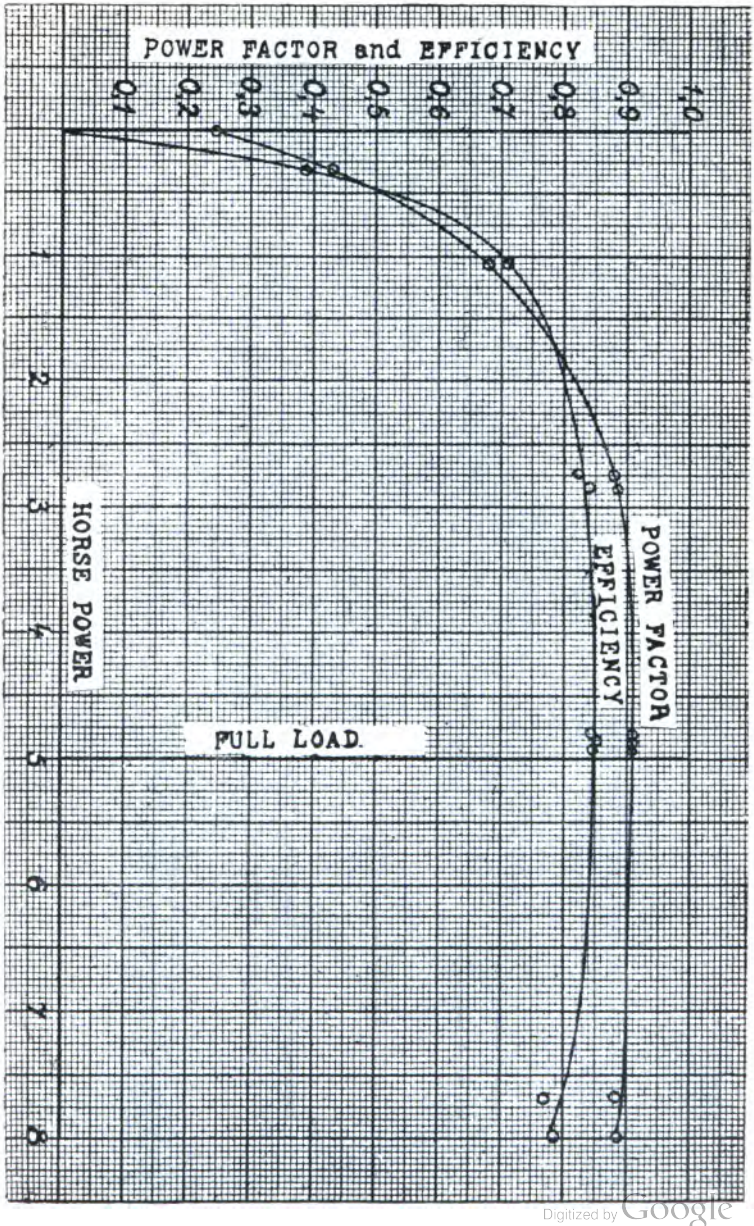

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FIG. 152.—PERFORMANCE OF 5 H.P. INDUCTION MOTOR.

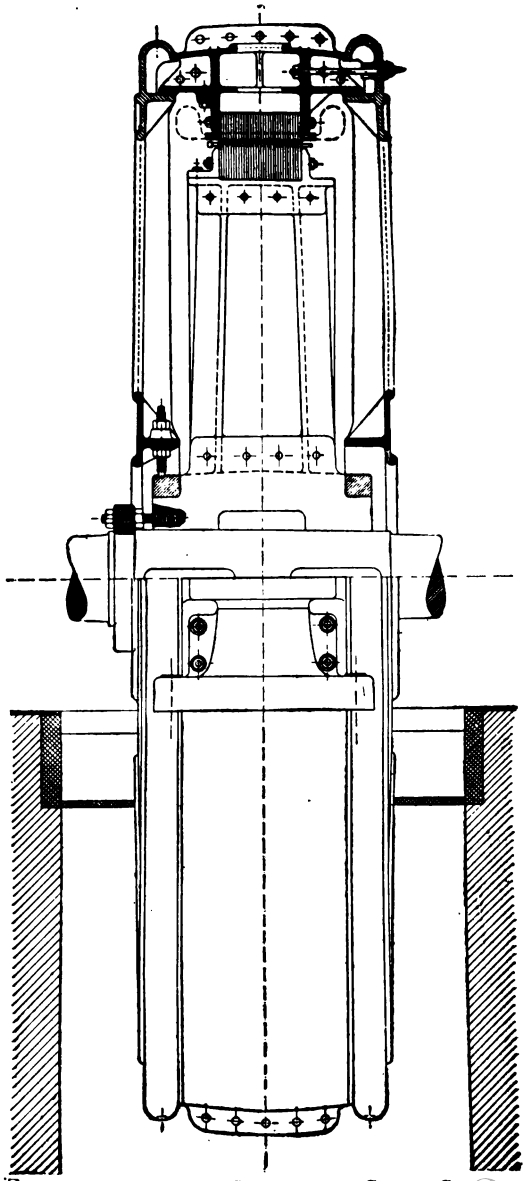

FIG. 153.—500 H.P. LAHMEYER SLOW SPEED INDUCTION MOTOR (SECTION).

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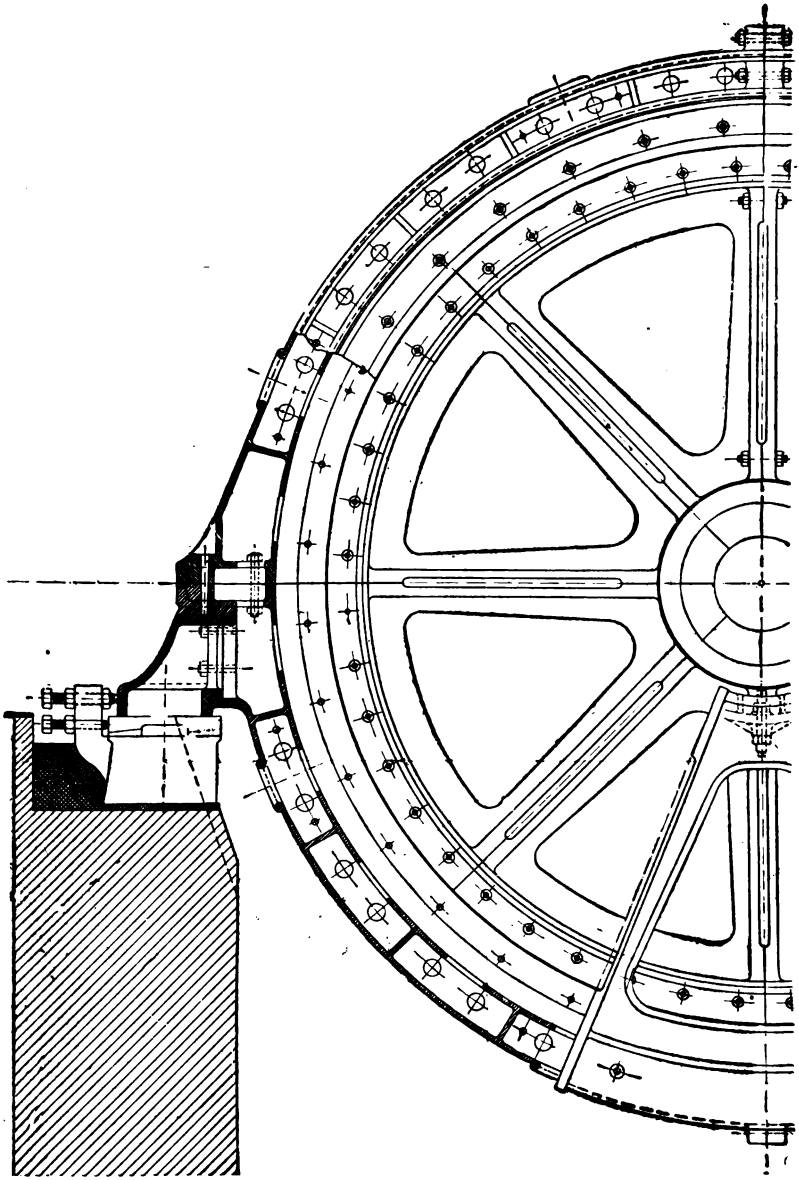

FIG. 154.—ELEVATION LAHMEYER 500 H.P. INDUCTION MOTOR.

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TABLE XXII. — 500 H.P., 25-CYCLES, 5,000-VOLT, 3-PHASE MOTOR, WITH Y CONNECTED STATOR.

B.H.P.	500
Volts per phase	2800
Revs. full load	97 per minute
,, light ,,	100 ,, ,,
Slip at full load	3 per cent.
Efficiency at full load	91½ ,, ,,
Power factor ,, ,, ,,	.92
Stator poles	30
Stator slots	450
Conductors per stator slot	8
Amperes per phase	51.3
Current density in stator conductors	1250 amps. per sq. in.
Bore of stator	120 inches
Width ,, ,,	25½ ,,
Weight of stator stampings	8200 lbs.
,, ,, ,, copper	1900 ,,
Diameter of rotor	119.86 inches
Width ,, ,,	25.5 ,,
Number of rotor slots	630
Weight of rotor stampings	7900 lbs.
,, ,, ,, copper	1400 lbs.
Watts per revolution	3880
Output co-efficient	94
Total weight of machine	21½ tons.

A slow-speed machine of this type, built by the Lahmeyer Company, is illustrated in Figs. 153 and 154, and another similar machine directly coupled to a winding gear at a coal mine in Dortmund, Germany, is shown in Fig. 155. This motor is by the Allgemeine Elektricitäts Gesellschaft, Berlin (The Electrical Company, London), and is one of many employed for this purpose on the Continent.

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The method of building small motors differs little, the stampings being generally held in the cast-iron case by bolts passing through the laminations and through a cast-iron plate, as shown by Fig. 156, which shows the stator of a Johnson and Phillips motor before winding, the method of fixing the stampings being clear. The Bergmann Electrical Works, Berlin, have an ingenious method of assembling the laminations whereby the use of bolts is eliminated and

FIG. 155.—SLOW SPEED THREE-PHASE MOTOR WORKING WINDING GEAR AT COAL MINE.

a very solid construction secured; when all the laminations have been assembled they are pressed together by a hydraulic press and a steel ring similar to a piston ring sprung in between the laminations and lugs on the cast-iron stator frame. This firm have also patented a most interesting rotor winding for machines with short circuited rotors: the feature of this is that it entirely

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FIG. 156.—UNWOUND STATOR CORE OF JOHNSON AND PHILLIPS' POLYPHASE MOTOR.

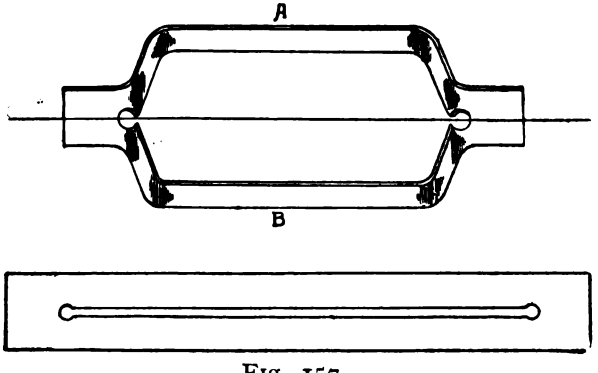

FIG. 157.

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eliminates the joints so common yet undesirable in the squirrel-cage rotor by making what are practically solid copper bars, resembling former wound coils for direct current machines, out of strip copper. The lower sketch, Fig. 157, shows the piece of sheet copper with the narrow slot along the centre. This is then placed in a machine, which stamps the strip into the shape shown in the top sketch, and which now resembles a former wound armature coil for a direct current machine. There are, of course, two bars in each slot, A being the top bar in one slot, and B the bottom bar in another, the distance between A and B being approximately

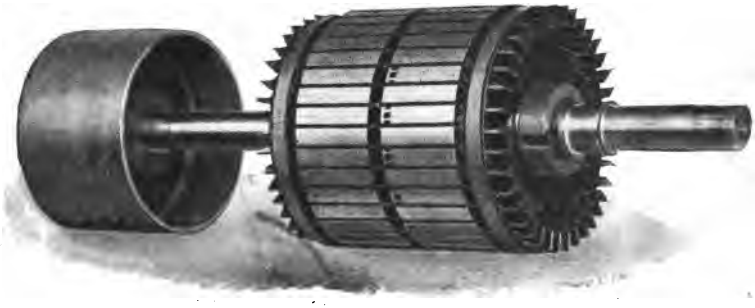

FIG. 158.—SHORT-CIRCUITED ROTOR OF BERGMAN N THREE-PHASE MOTOR WITH BAR WINDING.

equal to the pole pitch of the rotor winding. Fig, 158 shows a short-circuited rotor with this jointless winding.

Ventilation plays an important part in determining the output of inducton motors, as, indeed, it does in any motor ; but in the case of alternate current motors the carcase lends itself better to efficient ventilation. The cast-iron frame or housing, as Americans call it, is generally a more or less open frame sufficient to give mechanical support to the bearings and laminations; these latter, even in the case of comparatively small motors of two to three horse power, have one ventilating duct through

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the rotor and stator, while some firms make 5 horse power machines with two ducts. Core ventilation has become almost an art among one or two Continental firms, with the result that machines are small and cheap, yet have low temperature rise. A Bergmann motor shown, Fig. 159, will illustrate this. The Westinghouse Co. make machines with similar open frames. The British Thomson-Houston Co. carry ventilation still further in some small motors, by leaving a large area of the laminations exposed, as shown Fig. 160, a cast-iron frame having a few bars across it serving to support the endplates carrying the bearings. This machine has a wound rotor, the slip rings being outside the bearing bracket and enclosed by a sheet-iron cover, the handle for short-circuiting the slip rings and lifting the brushes being seen outside the case.

Some firms assemble the stator of their larger polyphase motors in a cast-iron frame, which does not support the bearings. An example of one of Messrs. Bruce Peebles' 100-h.p. two-phase motors is shown, Fig. 163. The stator, as will be seen from Fig. 161, has six poles and eight slots per pole and phase, making a total of 96 stator slots. The synchronous speed at 50 cycles is, therefore, 1,000 revolutions per minute.

The stator, Fig. 161, is assembled in a cast-iron frame, which has feet cast upon it to rest on the edges of the bedplate. Another method of carrying the stator adopted by the Westinghouse Co. will be shown later. Fig. 162 shows the rotor of this machine.

The Westinghouse Co. assemble the stator stampings in a cast-iron frame without the feet shown in Fig. 161. It is then placed inside the cast-iron frame shown, Fig. 164. This frame carries the bearings, and such an arrangement, particularly in the case of large motors, has many structural advantages. It will be noted that this method of carrying the bearings bears some resemblance to that shown, Fig. 25, generator section as an example of the practice of one or two European firms in connection with their slow-speed alternators.

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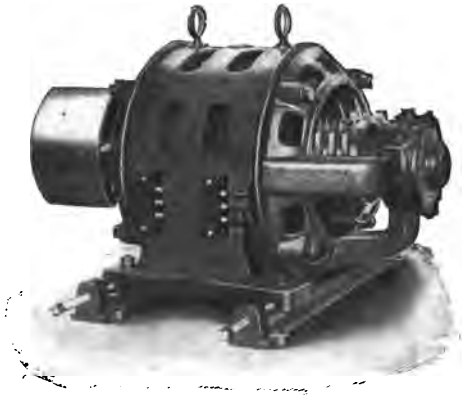

FIG. 159.—50 H.P. BERGMANN THREE-PHASE MOTOR RUNNING AT 1,445 REVOLUTIONS PER MINUTE.

FIG. 160.—BRITISH THOMSON-HOUSTON INDUCTION MOTOR.

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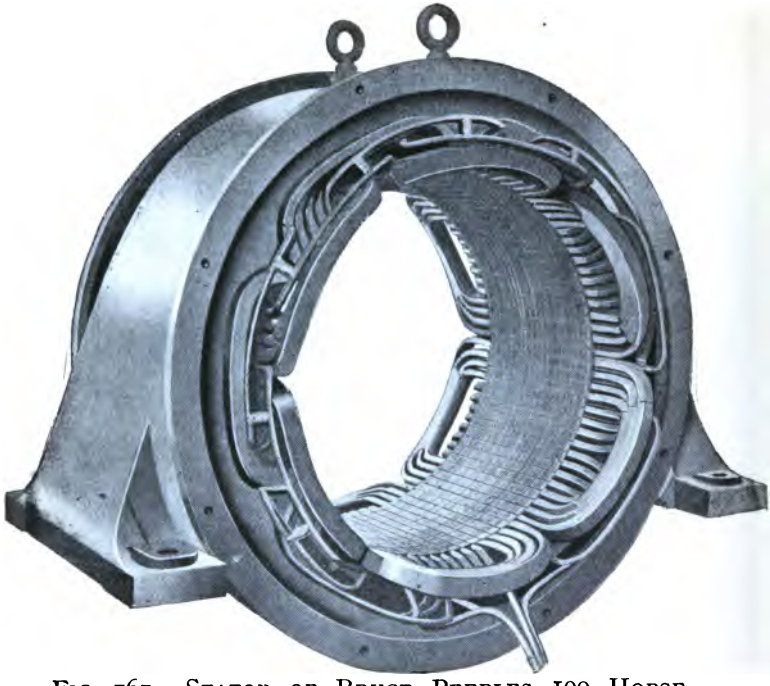

FIG. 161.—STATOR OF BRUCE PEEBLES 100 HORSE-POWER TWO-PHASE MOTOR.

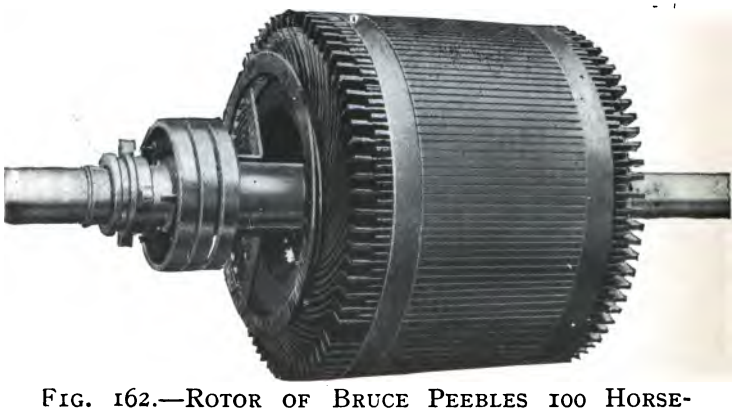

FIG. 162.—ROTOR OF BRUCE PEEBLES 100 HORSE-POWER TWO-PHASE MOTOR.

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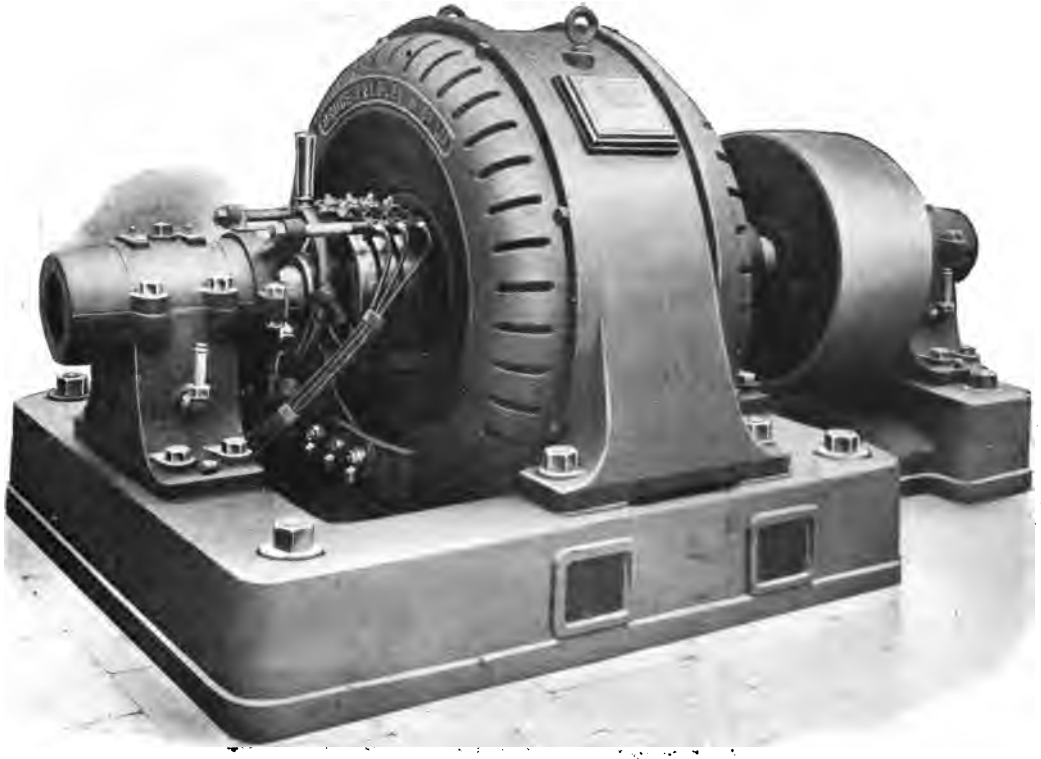

FIG. 163.—100 HORSE-POWER BRUCE PEEBLES TWO-PHASE MOTOR WITH THREE BEARINGS.

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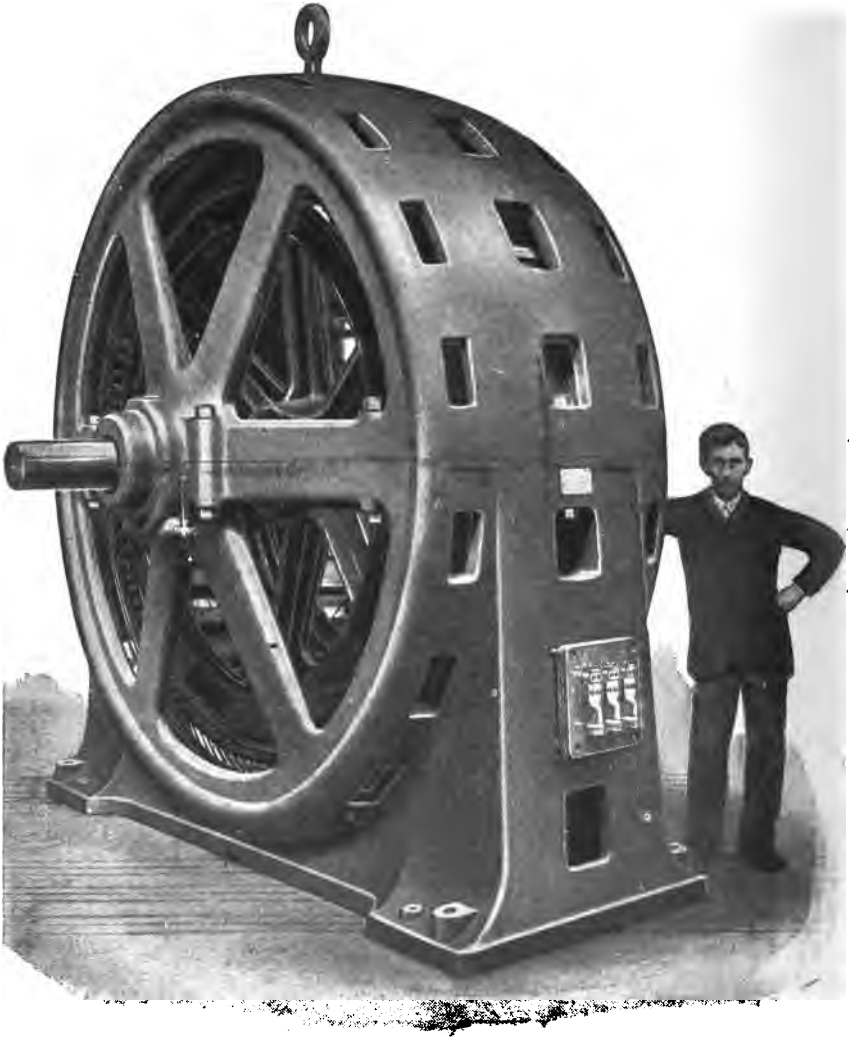

FIG. 164.—WESTINGHOUSE 500 HORSE-POWER THREE-PHASE INDUCTION MOTOR.

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A three-phase induction motor with short circuited rotor by the Electric Construction Company, Wolverhampton, is shown, Fig. 165. The stampings are

FIG. 165.—THREE-PHASE MOTOR BY ELECTRIC CONSTRUCTION COMPANY.

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assembled in a cast iron frame similar to Fig. 161, and the end plates carrying the bearings are bolted to this frame. The noteworthy feature of this motor is the fact that the rotor has a double winding similar to

FIG. 166.—ROTOR OF E.C.C. PATENT POLYPHASE MOTOR.

that described and illustrated (page 224, Fig. 138), the only difference being that instead of two windings, one of high and another of low resistance, both of which are short circuited, the low resistance winding

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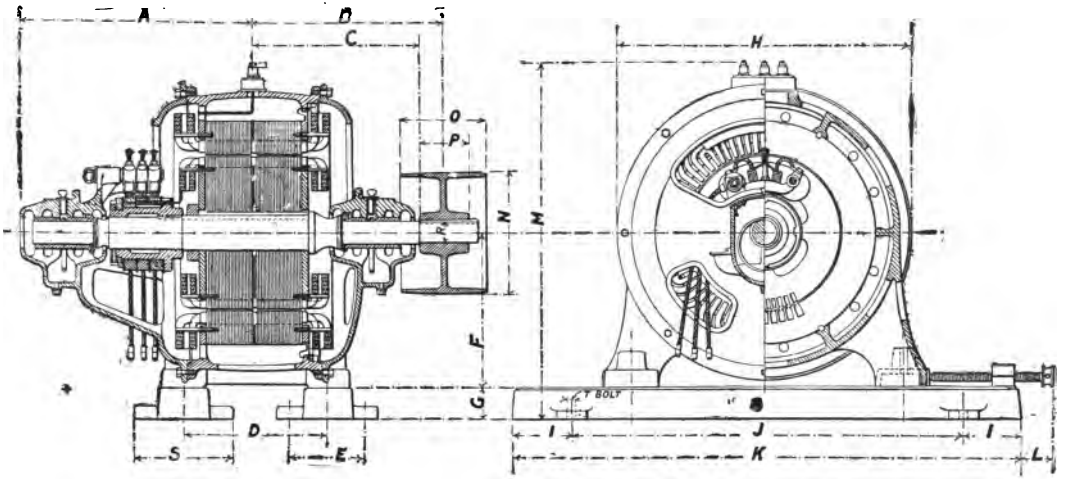

FIG. 167.—BRUSH ELECTRICAL ENGINEERING COMPANY'S POLYPHASE MOTOR WITH WOUND ROTOR.

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has an ordinary polar winding, as if intended for a wound rotor, but short circuited at the ends, the plain short circuited winding which is superimposed thereon, being of the high resistance short circuited type as already described, page 224. At starting the stator windings are connected so that the rotating field is continuous in one direction, but one half of each phase is reversed as compared with the other half; the effect of this on the corresponding polar winding of the rotor is nil, so that no current is induced in the latter. As, however, the short circuited rotor winding is not polar wound it is uninfluenced by the same flux distribution as the polar winding, and

FIG. 168.—UNWOUND ROTOR OF JOHNSON AND PHILLIPS TWO-PHASE MOTOR.

the field will consequently induce currents in the short-circuited rotor which will cause the motor to run up to speed with full load torque and comparatively small line current. Fig. 166 shows the rotor of the machine.

The rotor stampings in the case of small machines are generally slipped on to the shaft much the same way as the stampings of small direct current motors. This will be clear from Fig. 167, which shows a Brush three-phase motor with wound rotor. Larger motors have the stampings carried on a spider, the general arrangement of which will be clear from Fig. 168.

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CHAPTER XXI.

The Speed Control of Induction Motors.

We have hitherto dealt with the induction motor at speeds less than that corresponding to full speed and load, when starting only. We will now consider it under varying speed, because in the industrial applications of the induction motor variable speed is a necessity; for instance, in the case of cranes, elevators, and in railway working.

It has been shown that starting may be effected either by varying the impressed stator pressure by means of an auto transformer in the case of motors with short circuited rotor, and by rotor resistance in the case of motors with a wound rotor. Both these methods can be, and are, employed for speed regulation, but the variable rotor resistance is most usual because of its greater flexibility and adaptability to motors of usual design. The auto transformer method of varying the speed has the disadvantage that it is only satisfactory with motors specially designed for small magnetic leakage, because of the enormous rotor currents tending to increase the leakage and so reduce the flux interlinked with the rotor winding, and, therefore, the torque. The necessity for bearing this point in mind involves modifications, especially in the design of the slots and air gap, that make motors when designed for this purpose quite special. Hence practice has tended to drift in the direction of machines with wound rotors and secondary resistance, though, in addition, motors have been built in which the number of stator poles may be changed either by regrouping the stator windings or by having two or more machines, each having a different number of poles, mounted on the same shaft, and, last, by having two motors in cascade or tandem, these may or may not have the same number of poles. The machine with a wound rotor will first be briefly considered. Returning to Figs. 145 and 146, it will be seen that the effect of increasing the rotor resistance by the

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addition of an external resistance is to *lower* the speed at which maximum torque may be obtained, and the resistance in series with the rotor may be increased till a point where the speed is reduced to zero with full load torque. It is therefore only a question of proper rotor resistance to obtain gradual variations of speed from normal full load speed down to zero. It should be noted that as horse power is the product of torque and speed, the horse power of the motor is reduced in proportion to the reduction in speed, but the watts taken by the stator winding are not reduced, because the difference between the horse power of the motor at the lower speeds (*i.e.*, torque × revolutions) and the actual horse-power input to stator, is wasted in the rotor resistance. This waste in the rotor resistance goes on increasing till the speed reaches zero, when practically all the input to the stator, less, of course, the iron and copper losses, is dissipated as heat in the regulating resistance. At zero speed the motor acts practically as a transformer, with all the secondary output wasted in heating the resistance. The inefficiency of this method of regulating the speed is therefore apparent.

The fact that the speed of the motor is determined by the number of stator poles, has led to the use of motors with a switch for changing the number of stator poles: such as, for instance, on a 50 cycle circuit, a machine with four poles will run at 1,500 revolutions per minute, with six poles at 1,000 revolutions, and with eight at 750 revolutions. This may be effected by having the stator poles grouped so that an eight-pole machine may be made into a four-pole motor by reversing the polarity of every alternate pole. This is easily effected by tapping out from the middle of each phase, so that the change may be effected by taking the three ends of the normal winding to one side of a three-pole throw over switch, the tappings to the other side. When the switch is on one side the motor is four-pole, and on the other eight-pole, giving no load speeds of 1,500 and 750 respectively. With the smaller number of poles the power factor will be rather lower than at eight poles.

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The output of the motor will obviously be doubled with the doubling of the speed. The $C^2 \times R$ losses will be increased but little at high speed, the small increase being due only to the greater magnetising component, as the current density in the coils is nearly the same in both cases ; although twice the current passes into the motor as a four-pole machine at twice the normal speed and horse-power, the fact that the copper section is doubled will be apparent.

The fact that we have reduced the turns in series to one-half when changing from eight to four poles will be noted, and that this does not reduce the back E.M.F. in proportion is apparent from the fact that the magnetic induction per pole and phase has now been doubled.

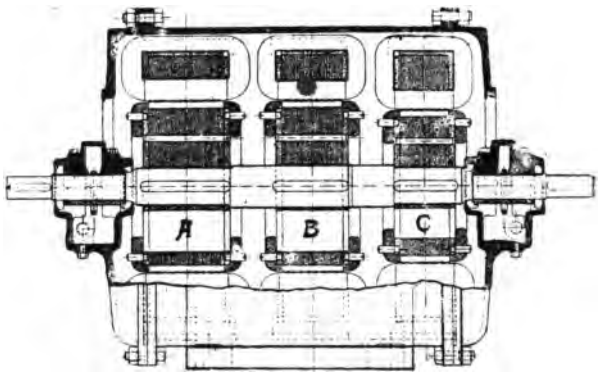

FIG. 169.—WUST AND CO.'S VARIABLE SPEED MOTOR.

The next method—that of having several motors mounted on one shaft, each motor having a different number of poles—was introduced on the Continent by Messrs. Wust and Co. about the year 1901. A section of such a machine is shown in Fig. 169, the dimensions of each machine being determined in the ordinary way. For instance, if a 10 h.p. motor, to give three speeds of 1,500, 1,000, and 750 revolutions respectively is wanted, the 750 revolution motor

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would, of course, be largest. It is marked A on the illustration; B is the 10 h.p. 1,000 revolution machine, and C is the 10 h.p. 1,500 revolution motor

Not only can the speeds already mentioned be obtained with economy, but by other combinations intermediate speeds can be obtained. These are set forth in Table XXIII., which shows that the speed control is fairly satisfactory, if the capital cost of the motor and the complication of the controlling apparatus are left out of account.

TABLE XXIII. — SPEED CONTROL OF COMBINATION MOTORS WITH VARYING NUMBER OF POLES.

1,500 revolutions with four pole motor only.
1,060 revolutions with four and six pole motors in parallel.
1,000 revolutions with six pole motor only.
825 revolutions with four, six and eight pole motors in parallel.
790 revolutions with six and eight pole motors in parallel.
775 revolutions with four and eight pole motors in parallel.
750 revolutions with eight pole motor only.

The results when the motor was loaded up to maximum power are given in Table XXIV., with the corresponding slip.

TABLE XXIV.—SPEED AND MAXIMUM POWER OF COMBINATION OF MOTORS WITH VARYING NUMBER OF POLES.

Maximum H.P.	Speed.	Slip.
11½	930 revs.	12½% with four and six pole motors in parallel.
14	695 „	11½% with six and eight pole motors in parallel.
11	670 „	13½% with four and eight pole motors in parallel.
18	695 „	16 % with four, six and eight pole motors in parallel.

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When uncombined either motor gave about ten h.p. with about ten per cent. slip.

The cost of motors arranged in this manner is very great, being, for a machine consisting of three motors, about 85 per cent. of the sum of the cost of three separate machines. It will perhaps be found useful in machine shops or for printing press purposes, where polyphase motors with wide and economical speed control are wanted, regardless of cost.

The last and most interesting method is cascade or tandem control. It is in extensive use both for railway and industrial purposes. Messrs. Brown Boveri, of Baden, and Messrs. Ganz and Co., of Buda-Pesth, have employed this system for many years and some of the German electrical concerns have used the system for large rolling mill motors. The general principle is based on the fact, already alluded to, that the periodicity of the rotor current is proportional to the slip, and to the fact that an induction motor, when driven above the speed of the rotating field—*i.e.*, with negative slip—becomes a generator and will give off a good deal of power. The performance of the induction motor as a generator will be dealt with later, meanwhile this fact should be kept in view. Take Fig. 170 as indicating two motors coupled rigidly together on a common shaft—the stator of the motor A being supplied from the line in the usual manner, while the stator of the motor B is supplied from the rotor of A; or in some cases the current from the rotor of A is supplied to the rotor of B. The former is common practice with Messrs. Ganz and Co., but is only applicable when the ratio of primary to secondary is 1 to 1. This is not always the case, and if not, the rotor of A is then connected to the rotor of B, which will be more or less similar. The stator of B is assumed in this case to be connected to the rotor of A, there being a 1 to 1 ratio between the stator and rotor windings. The speed of the stator field of B will obviously be equal to the periodicity of the rotor currents in A; and if we take, for example, half speed and a periodicity in A of 50 cycles, we have the periodicity of B as 25 cycles.

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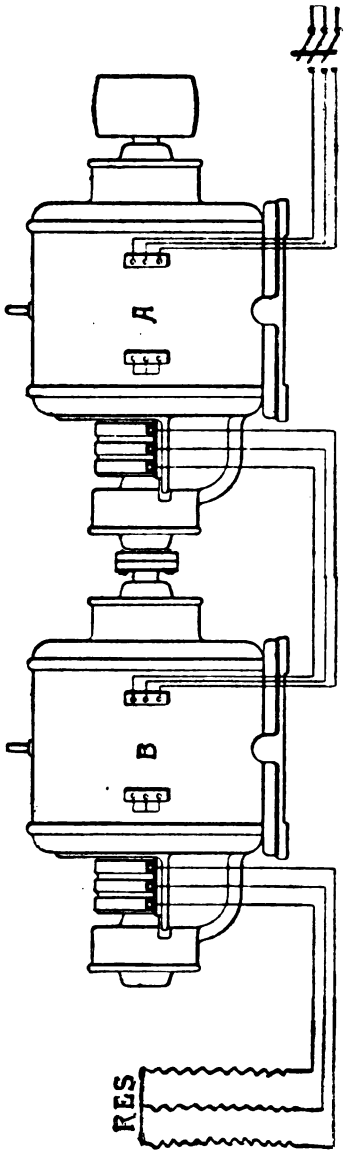

FIG. 170.—POLYPHASE MOTORS IN CASCADE.

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Now the effect of this stator field on B will be to endeavour to make the rotor run at about synchronous speed, which will be half speed; the fact that the two machines are rigidly coupled together prevents them gaining any greater speed than half speed when so connected, as the effect of an increase in speed would be that the periodicity of the rotor of A would fall, and, as the rotor of B would be running at the same speed as A, B would become a generator as it would then have negative slip—*i.e.*, the speed of the rotor B would be greater than that corresponding to the speed of its stator field; that is, the rotor of B would be running above synchronism, and therefore the stator would give current back to A by reason of its higher back E.M.F., thus acting as a generator and braking A. If the speed is, however, below half speed the machine A acts partly as a motor and partly as a generator, because the low periodicity currents in its rotor are supplied to the stator of B which turns this energy into work, while the other half of the energy supplied to A is given out as work on the shaft. Thus the two motors in cascade give out all the energy supplied to the stator of A as B.H.P. at half the normal speed, almost exactly like two direct current motors in series. The actual sequence of operations on the polyphase railways equipped by Messrs. Ganz and Co. is something like the following:—

Controller step I., stator A on line, rotor of A to stator of B, rotor of B on resistance.

Controller step II., stator A on line, rotor of A to stator of B, rotor of B short-circuited.

Controller step III., stator A on line, rotor of A on resistance, B cut out altogether.

Controller step IV., stator of A and B on line, with resistance in rotors.

Controller step V., stator of A and B on line with resistance short-circuited.

A procedure not unlike series parallel control in direct current practice.

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An interesting combination of the foregoing system of cascade connection and the method of changing the speed by changing the number of poles is in use in the Sandviken Ironworks, in Sweden, where there is a 150 h.p. three-phase motor driving the rolling mill. This is a case where speed regulation is useful and it is obtained by a combination of two motors, as shown in Fig. 171. The main motor is wound for 14 poles, and gives a speed of 428 revolutions per minute with 50 cycles; the auxiliary motor is wound for two or four poles.

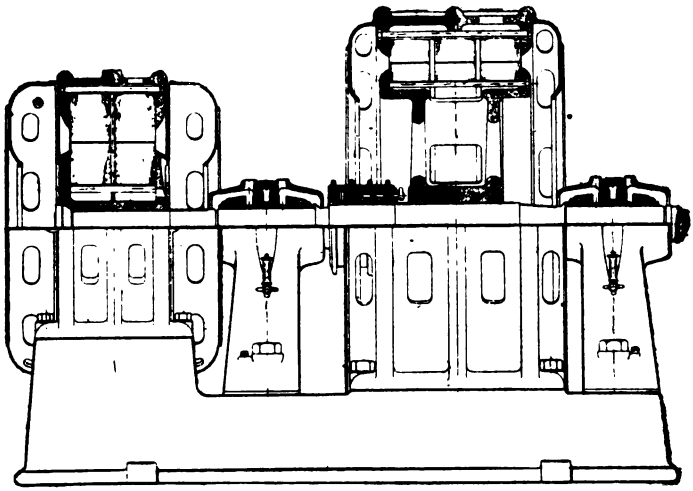

FIG. 171.—VARIABLE SPEED POLYPHASE MOTOR.

To get 375 revolutions the auxiliary motor is coupled in tandem (cascade) as a two pole motor and for 333 revolutions the auxiliary motor is coupled as a four pole motor and is in cascade to the rotor of the main motor. The three speeds are obtained with only a small variation in efficiency as the following table will show.

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TABLE XXV.—150 H.P. 3-PHASE ROLLING MILL MOTOR.*

Speed per minute.	Power factor.	Efficiency.	Remarks.
428 revs.	.92	89%	Main motor only.
375 ,,	.83	88%	Main motor and auxiliary motor in cascade as two pole machine.
333 ,,	.81	87%	Ditto, but auxiliary motor as four pole machine.

* Compiled from article by E. Danielson in the "Electrotechnische Zeitschrift," January 21, 1904

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CHAPTER XXII.

The Compensated Induction Motor and Non-Synchronous Generators.

The fact that an induction motor will become a generator if driven above synchronous speed has already been pointed out, but this generator action is quite distinct from, and due to somewhat different causes than the generator action of the first of two motors in cascade or tandem. That the first of the two motors in tandem acts as a generator is due to the fact that if the rotor runs in the field due to the stator but is prevented from attaining anything near synchronous speed by the conditions of the load, so that its speed, it may be assumed cannot become greater than, say, half-speed, the rotor will have E.M.F. and current induced in it proportional to the ratio of the primary and secondary windings (stator and rotor), to the flux interlinked with the rotor windings, and having a periodicity (in the case of half-speed) of half the stator periodicity. This rotor current may be conveyed to an external circuit such as another motor, as already described in cascade working. The action, while resembling a generator, is not really so. It is more closely analogous to a periodicity changer or to a transformer, where, of all the electrical energy supplied to the stator, half reappears as mechanical power at the motor shaft, and half has been transformed into electrical energy, reappearing at the rotor slip rings at a different periodicity (half in this case) and a different voltage, probably half also.

The non-synchronous generator differs, however, from the foregoing in that the current which it gives off does not come from the rotor but from the stator.

When an induction motor connected to a circuit, and running under normal conditions, is speeded up to beyond synchronous speed, the stator begins to *give off* current, the magnitude of this output depending upon the speed at which the rotor is driven. The reason for this is as follows :—When the machine is running below

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synchronous speed, the relative rotation of the rotor and stator fields is that the former is slower than the latter, that is, if the slip is 5 per cent. it is equal to rotating the rotor *backwards* at 5 per cent. of full speed, with a fixed stator field. Now if the speed of the rotor be increased to, say, 5 per cent. above synchronous speed, it will be equivalent to running the rotor *forward* at 5 per cent. of full speed with a fixed stator field. During this change from below synchronous speed to above it, there will be changes in the rotor current. Just as the rotation of the armature of a direct current dynamo first in one direction then in another produces a current flowing in one or other direction corresponding to the changes in direction of rotation, so the rotor currents in the above case will flow in one direction when the machine is rotating below synchronism, and gradually die down as the rotor reaches synchronous speed, at which speed there will be no rotor current as the rotor winding cuts no flux.

If mechanical power sufficient to raise it above synchronous speed is supplied, the rotor current will again rise, but this time in the opposite direction, due to the change in the relative speed of rotor and stator. This reversed rotor current will give rise to a reversed stator current, just as in the case of a transformer supplying current to the secondary in the reverse direction will cause the primary current to reverse also, and if a sufficient E.M.F. and current is supplied to the secondary, the primary will actually give current back to the line. Our induction motor now does so; for while we do not supply electrical energy to the secondary to cause it to act like a reversed transformer, we supply mechanical energy which, owing to the relative action of the two moving fields, causes it to give power back to the line. The relation of the E.M.F.'s being as follows: As a motor, the watt current input, which is in phase with the supply volts, is in opposition to the back E.M.F. of the stator, but when the motor is driven above synchronous speed the reversed (secondary) rotor current sets up a corresponding reversed (primary) stator

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current, and this reversed primary current is now in *opposition* to the supply pressure and therefore in phase with what was formerly the stator back E.M.F. The induction motor therefore becomes a generator by reason of what was formerly the back E.M.F. becoming an active voltage.

The reversibility of the induction motor is now evident. It should also be noted that the machine as

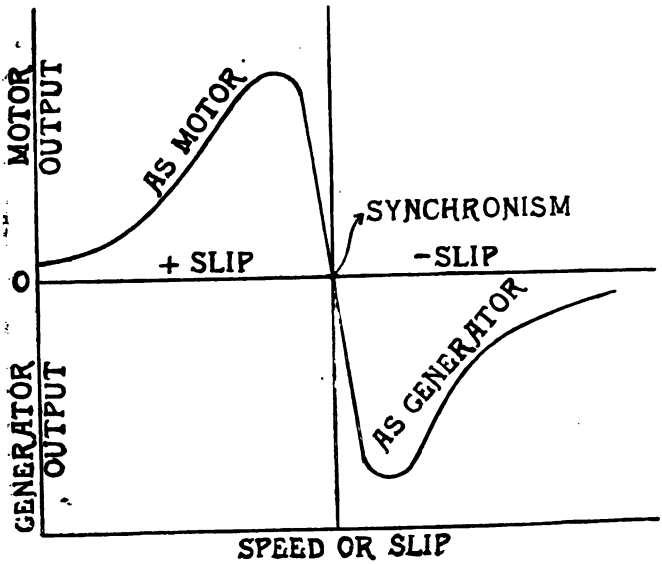

FIG. 172.

a generator possesses all the characteristics of the motor ; its maximum output and speed variation between no load and full load remain the same, so that by drawing the curve of output as a motor we have the output of the machine as a generator. This is shown in Fig. 172.

The machine is not, of course, self-exciting, the magnetising component of the current has to be supplied from an external circuit ; indeed, unless the stator of the

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induction motor is actually connected to a circuit in which there is a current it can never become a generator, as the rotor current is due to the stator current and not *vice versa*, consequently there must first be a stator current and the generator action consists in reversing the rotor and stator active E.M.F.'s. It is therefore necessary to have a synchronous alternator sufficiently large to supply the wattless magnetising current and to set the periodicity. It should be noted in connection with induction generators of this type that the periodicity is independent of the speed, and that the output is proportional to the speed up to a certain point, just as the output of an induction motor is proportional to the slip, and subject to the same limitations, as will be apparent from Fig. 172.

Mr. Heyland, whose work in this direction stands as a monument to his ingenuity and thorough knowledge of the subject, has, however, grasped the fact that the high E.M.F. necessary to send the wattless (magnetising) current through the stator winding is due to the self-induction of these windings; and in point of fact the same magnetising current could be sent through the windings by only a few volts, were the current direct instead of alternating, the balance being necessary to overcome the back E.M.F. of self-induction; indeed, the voltage necessary to drive the magnetising current through the winding falls off in proportion to the reduction in the periodicity. He therefore hit upon the idea of supplying the magnetising current at the low periodicity of the rotor current instead of at the line periodicity. As has already been pointed out the periodicity of the rotor current is, under full load, small, equal to that due to the slip only, hence in the case of a 50-cycle machine having 5 per cent. slip at full load the periodicity of the rotor current will be about $2\frac{1}{2}$ cycles per second. This will be the same whether the rotor revolves 5 per cent. below synchronous speed, as a motor, or 5 per cent. above synchronous speed, as a generator.

In Heyland self-exciting machines, both motors and generators, the low periodicity rotor current is supplied

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not by the transformer action of the motor, *i.e.*, supplying the magnetising current to the stator at full voltage and periodicity and then the low periodicity rotor current induced therefrom by the transformer action of the motor, but it is supplied direct to the rotor at a low periodicity by means of a commutator which acts really

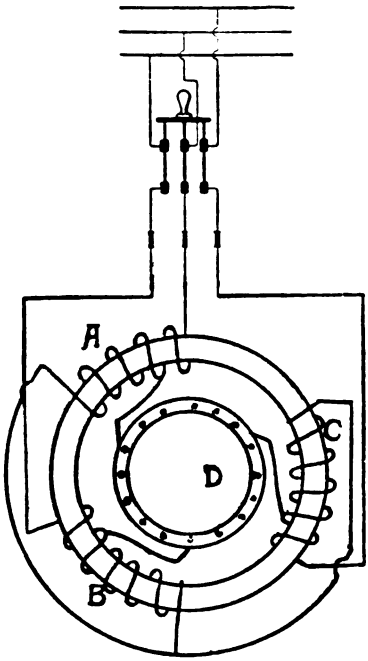

FIG. 173.—ELEMENTARY HEYLAND SELF-EXCITING INDUCTION GENERATOR.

as a kind of frequency changer. These low periodicity rotor currents supply the working field of the motor, so that instead of the stator supplying the working flux, the rotor does so, thus the stator only has to deal with the watt component of the output, and (if a generator)

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the wattless currents due to inductive apparatus on the circuit. The most elementary type of Heyland self-exciting non-synchronous motor or generator is shown diagrammatically (Fig. 173), where A B and C are the stator windings, D the rotor with a squirrel cage winding,

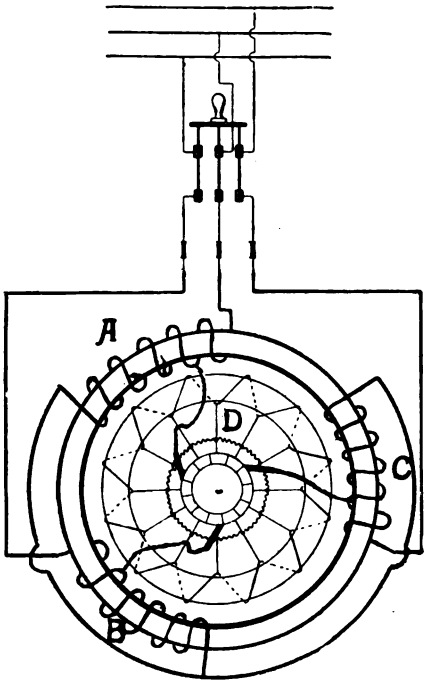

FIG. 174.—HEYLAND SELF-EXCITING POLYPHASE GENERATOR, WITH DRUM WINDING AND COMMUTATOR.

and brushes on the short circuiting rings. If the machine is intended to operate on high pressure circuits a transformer is necessary to get the low rotor E.M.F. If the pressure is such as is usually used for local lighting and power circuits a tapping off the stator winding, as shown,

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is all that is necessary. If the rotor revolves and there is also a current in the stator winding producing a rotating field, the frequency of the current passing from the tappings on the stator winding into the rotor *via* the brushes, will be proportional to the rotor speed, it will be equal to the stator periodicity when the rotor is at rest, and practically a direct current when the rotor revolves in synchronism with the stator field, and at 5 per cent. slip between rotor and stator, the periodicity will be 5 per cent. of the periodicity of the stator current. Moreover, if the speed of the rotor is 5 per cent. less than synchronism, the direction of the currents in the bars of the rotor winding is in a certain direction, as the rotor speeds up towards synchronism the periodicity gradually falls, and the current becomes continuous. As the rotor begins to run above synchronism the current becomes alternating again, but this time in the reverse direction, as already explained, when describing the action of the induction motor above synchronism. It must not be forgotten that the actual rotor currents due to the rotor bars cutting the stator field remain the same as they would in the ordinary induction motor, the magnetising current passing into the rotor through the brushes is separate and distinct, just as in the case of the ordinary induction motor the stator magnetising current is quite distinct from the watt current, the high periodicity magnetising current in the stator being simply replaced by a low periodicity magnetising current in the rotor.

It is now apparent that, as in the case of the ordinary induction motor, the magnetising current and ampere turns are those necessary to produce the rotor flux plus leakage flux, while in the case of a compensated machine, the amperes and ampere turns are those necessary to produce the rotor flux only, hence in constructing an induction motor the ampere turns on the stator field are less, and the ampere turns on the rotor are *increased* by the amount necessary to produce the rotor flux.

Fig. 174 shows a practical method of exciting the rotor where the rotor windings, which in this case may

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be a drum winding, are connected to segments of a commutator, these segments being shunted by connectors of comparatively low resistance. The function of these connectors is to short circuit the ends of the rotor winding, and so permit the usual rotor currents to flow, the magnetising current being supplied through the three brushes as already described. In the more recent Heyland non-synchronous alternators the rotor has been wound with two windings as shown at RW, Fig. 175. These are short-circuited at their inner

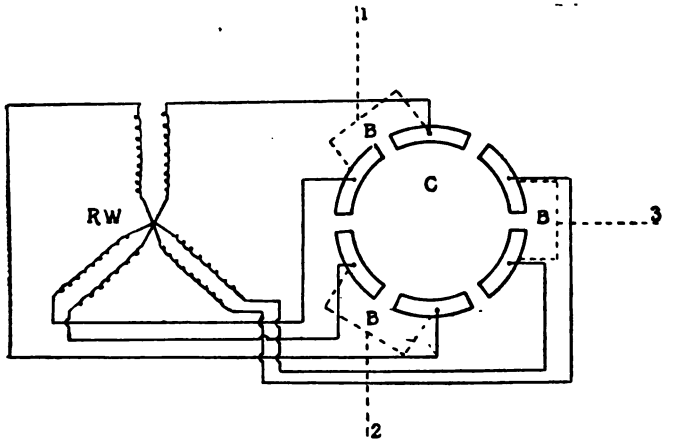

FIG. 175.—COMMUTATOR CONNECTIONS—HEYLAND ALTERNATOR.

ends, and the magnetising current is supplied through the brushes, B, which are the width of one segment; thus either one or both windings are always in circuit, and there can be no sparking at the commutator as the two windings are either always in parallel in the circuit, or when one segment is leaving the brush the self-induction of one winding is balanced by the mutual induction of the other, both being in the same slots; the connections to the stator being made at 1, 2, or 3.

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We are now more particularly concerned with the action of these compensated machines as generators, but before leaving the subject it will be as well to refer to the effect of such windings in the case of induction motors. It is possible to make an ordinary induction motor with a power factor of unity at full load. Early in 1903, Professor Adams* read a paper to the American Institute of Electrical Engineers, in which he gave much interesting data *re* the performance of a 10-h.p. Heyland motor. These are summarised in Table XXVI., and other information of a corroborative nature was given in the *Electrical Review* during July, 1903.†

TABLE XXVI.—10-H.P. 3-PHASE 60-CYCLE 6-POLE HEYLAND COMPENSATED MOTOR.

	Line Amperes. Full load.	Line Amperes. No load.	Power factor. Full load.	Power factor. No load.
As ordinary Induction Motor	14	6	.86	.2
As Compensated Motor..	12¼	2	.99	.65

The no load current in the case of the ordinary induction machine was 43 per cent. of the full load current, and only 16 per cent. in the case of the compensated motor. The net result is that, while the consumer has undoubtedly got a motor which is slightly more complicated than the ordinary induction motor, the elimination of the wattless component, which shows a gain of about 15 per cent. at full load, must mean a saving of about 20 per cent. in plant and mains capacity to the supply authority, as the majority of induction motors are operated at about three-fourths of their maximum load, at which point the power factor is even lower than the figure given.‡ It must also be noted that in addition

* "Transactions of the American Institute of Electrical Engineers," May, 1903.

† George Hooghwinkle, in the *Electrical Review*, July 17-31, 1903. See also A. C. Eborall, in the *Electrician*, July 3, 1903.

‡ Not necessarily so.

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to increasing the plant capacity by the reduction in the magnetising current, the voltage regulation of the system is better.

The non-synchronous generator, as has already been noted, cannot be employed without a synchronous generator, which fixes the periodicity, and in the case of the simple induction motor driven above synchronism this generator must also supply the wattless magnetising currents. By compensating the

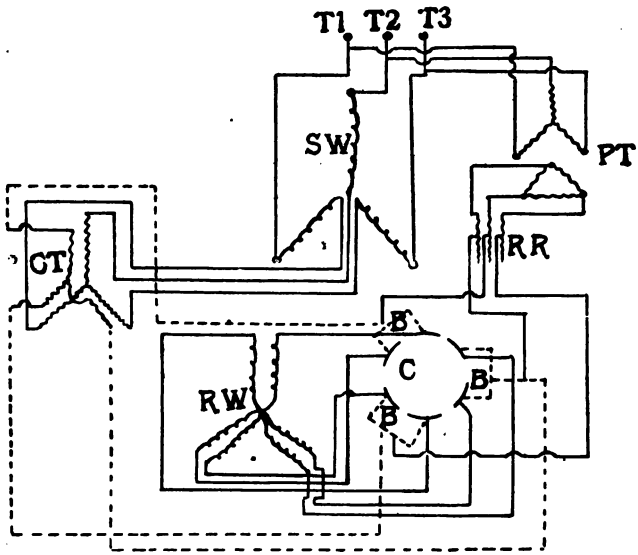

FIG. 176.

non-synchronous generator we not only do away with the necessity of supplying the wattless magnetising current, but also make the machine capable of handling the wattless currents in the system—it may even be compounded. The connections for doing this are shown in Fig. 176, where, as the generator is a high pressure machine, having terminals (T1, T2, T3), the rotor magnetising current is supplied in the manner already described,

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but transformed by the current and potential transformers shown (CT and PT.) The potential transformer has a delta connected secondary in order to maintain a phase difference of 90 degrees with the terminal E.M.F., that is to provide the compensating E.M.F. in phase with the flux, which, of course, leads the line pressure by 90 degrees. The compounding current may pass into the rotor either by the brushes (B) which carry the magnetising current, or by three additional brushes. The current transformer is for supplying the compounding current only, the other (P.T.) for excitation, and the E.M.F. of this current is regulated by the resistance (R.R.) The compounding of the generator is adjusted by moving the brushes, just as has already been described when referring to Heyland's compounded synchronous generators. The other reference letters in Fig. 176 correspond to those used in Fig. 175.

In addition to the reversed induction motor self excited, it is possible to use a standard induction motor; indeed, it has often been employed, as a synchronous generator, in which case the rotor, which usually has a three-phase winding, may have one phase excited by means of a direct current at suitable E.M.F. The latter is usually low—anything from 10 to 30 volts—as in normal operation the higher slip-ring voltage is due more to the impedance of the windings than to the ohmic drop.

This direct current produces a field which will have two, four, or more poles, depending, of course, on the rotor winding. If the rotor is driven by a prime mover, it will give off power like a synchronous generator. Moreover, the machine may be used on the circuit as a synchronous generator or as a synchronous generator or motor; as the latter it has all the properties of the synchronous motor as described in Chapter XVIII., with the additional advantage that it is self starting.

The author has frequently employed induction motors as synchronous generators with satisfactory results on loads of high-power factor. With low power factors the short air-gap of the induction motor enables the armature reaction to exert a serious influence on the

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pressure regulation, and in this respect they are unsatisfactory, though induction motors designed with synchronous operation in view should prove satisfactory.

CHAPTER XXIII.

Testing Polyphase Generators.

When an alternator has been completed certain tests are necessary to ascertain whether or not the machine fulfils the conditions of the specification, if there is one, or comes up to the expectations of the designer in the matter of temperature rise, regulation, &c.

Among the first things the designer wants to know is the relation between the field excitation and the terminal volts, *i.e.*, the saturation curve. It is a curve similar to Fig. 52, page 96, but as it is the relation between volts and ampere turns, the former being the ordinates and the latter the abscissæ, the curve bends over at higher values of excitation and voltage, as the increase of the magnetic induction and consequently the voltage does not keep pace with the increase in excitation, as the magnetic circuit becomes saturated. This curve enables the designer to check the leakage co-efficient, and if the first machine of a new series, supplies useful data as to the magnetic constants, &c.

The next step is to ascertain the synchronous impedance and reactance ED and DR, Fig. 51, page 95, and also the short circuit current. The latter is obtained by plotting the curve (Fig. 52, page 96). The next test is the light load and core losses of the alternator. The first is obtained by driving either by belting, or direct coupling a motor, preferably a direct current motor with copper gauze brushes, to the alternator, and making the necessary observations. Copper gauze brushes are preferable on the motor as then the $C^2 \times R$ losses due to contact resistance of the brushes are sufficiently small to be negligible, which is not by any means the case with carbon. Another precaution necessary in determining

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the motor losses is to measure its armature resistance at the *end* of the test, for by so doing the loss in the armature is more accurately determined. The exciter of the generator may be used to drive it, if more convenient. The difference between the input of the motor light, and when driving the alternator unexcited gives the loss due to friction and windage, and the additional input when the alternator is excited gives the core loss, eddy currents, and hysterisis; this should be taken at several excitations corresponding to various loads, the proper correction for $C^2 \times R$ loss with increase in the motor armature current being of course made. A motor 15–20 per cent. of the output of the generator is ample for this test; a smaller machine would do, but in order to obtain accuracy it is desirable to operate the direct current motor well under its normal load so as to avoid errors due to armature reaction.

If the alternator is driven by a belt from the direct current motor this should preferably be endless or have a butt joint. It is important, especially with an alternator whose armature possesses considerable inertia, to see that the speed remains practically constant for some minutes as otherwise the readings will be false, due to the influence of the energy of acceleration or retardation.

In measuring the output it will be apparent from Figs. 21 and 22, pages 54, 56, that the measurement of power in a two-phase circuit presents no difficulties, it being taken by an ordinary single phase wattmeter in each leg, the sum of these readings being the total watts. In the case of three-phase the procedure is somewhat different, and not quite so simple, as with low power factors one wattmeter gives negative readings, consequently the sum of the wattmeter readings does not represent power if the two-wattmeter method is employed.

The simplest way is, of course, to take the volts and amperes or watts of one *phase* and multiply the result by three if the load is balanced, if not, the watts per phase taken on three wattmeters is the next

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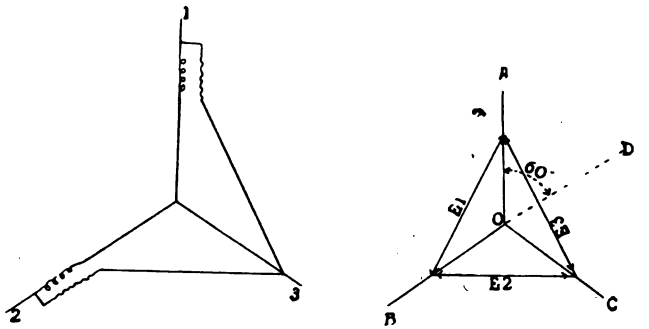
alternative. This, however, is usually impracticable, so the two-wattmeter method is generally used. This is shown diagrammatically (Fig. 177), where the lines are 1, 2, and 3, having the current coils of the wattmeter connected in 1 and 2 the E.M.F. coils connected 1–3 and 2–3, the sum of the two readings gives total watts when the power factor is over 50 per cent. If less, the conditions existing are those shown, Fig. 178, where under normal conditions with power factor unity, the phase relationship of the voltage and current per phase lie along the lines OA OB and OC, while the voltage between the lines would be represented by



FIGS. 177 AND 178.

E1, E2 and E3. So long as the current and E.M.F. are in phase, the current per phase will lie along the same lines as the E.M.F., but assume that the current lags 60 degrees behind the E.M.F. (Cos. 60° = .5) the phase relationship of the current is shown by the dotted line OD; the volts per phase now lie along OA and the current along OD. The line OA represents the phase of the current in the current coil of the wattmeter (Fig. 177) power factor unity, and it makes with the line E3 the angle A–E3, which represents the voltage across the volt coil of the wattmeter. This angle is approximately 150 degrees. Should the current

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be out of phase with the phase voltage, *i.e.*, instead of lying along the line OA, it is displaced 60 degrees from OA, *i.e.*, OD, then the angle which the current now makes with the voltage E3 is 90 degrees (60—150) and as the cosine of 90 degrees = 0, the wattmeter will read zero, because at this point the two currents, one due to the line current in the current coil and the other due to the line volts in the E.M.F. coil, reach their maximum at right angles to each other, and therefore produce no torque. If the angle of lag is greater than 60 degrees *i.e.*, the power factor is less than .5, the wattmeter readings should be subtracted, as then one wattmeter reads negative power.

It is now necessary to measure the total losses, which can be done in a variety of ways ; with small alternators it is not difficult to get a satisfactory load on a water resistance, the output being measured as detailed, though the results will be rather better than on an ordinary non-inductive load as a water resistance possesses capacity.

A method common with flywheel alternators for high E.M.F's is to oppose one group of poles against another, and short circuit the armature, by so doing an E.M.F. proportional to the difference between the two groups of poles will be induced in the armature, and a current proportional thereto will flow, opposed only by the synchronous reactance of the machine ; by so grouping the poles that full load current will flow results approaching closely to actual full load conditions can be obtained, and the result is satisfactory for all ordinary purposes.

The total core loss is rather lower than in practice as the two adjacent poles at each end of the group are of the same polarity, but the greater the number of poles the more insignificant does this become, and as this method has hitherto been applied only to flywheel alternators with many poles, the disadvantage is not serious. The armature reaction of such a combination of poles on an alternator is of importance, owing to the circuit being a purely inductive one, the current will be lagging, and the reaction of

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this wattless component will, of course, tend to reduce the effective flux in the larger number of poles, but if it lags in the generator portion of the machine, it will lead in the motor portion of the armature, as in the latter all considerations are reversed. The net result, is, however, so small as to influence the machine only to a slight extent. This test should be used for temperature

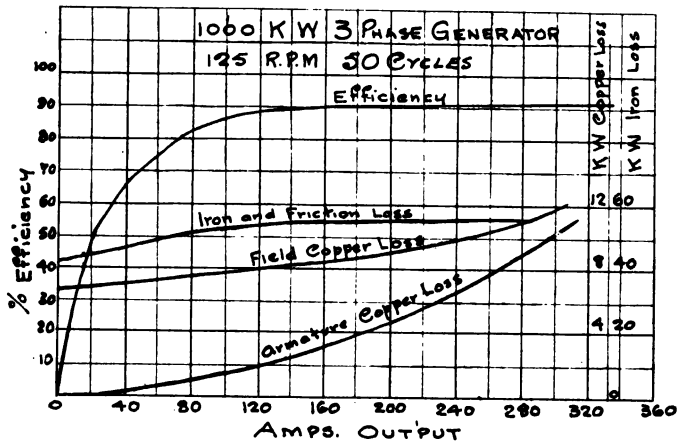

FIG. 179.

rise. As such a test can be made by driving the alternator with a motor large enough to supply only the internal losses, it can be applied to almost any size of flywheel alternator with only a small amount of power, and is consequently largely employed.

We now know how to ascertain (*a*) the saturation curve; (*b*) the synchronous impedance and reactance; (*c*) the light load and $C^2 \times R$ losses; (*d*) the excitation watts; (*e*) to make a test under conditions approximately equal to full load conditions. The further tests are: (*f*) field characteristic and (*g*) regulation. Both can be obtained simultaneously, and consist in plotting a curve showing the relation between the armature

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E.M.F. and armature current with constant field, the abscissæ being amperes armature, and the ordinates volts at armature terminals; two such curves are shown (Fig. 50), page 93. The wave form should be investigated either by means of an oscillograph or by a stop on the collector rings.

This influences the parallel operation of the machine, though separate experiments should be carried out on this when the generator has been installed among its neighbours. Before leaving the test plate, the alternator should, if possible, be tested for ability to withstand a short circuit. Owing to magnetic stresses, the armature frame is liable to deflect when these strains are suddenly applied, or the armature coils may be displaced. These points should be carefully watched before the machine is accepted.

The mechanical construction of the bearings, pedestals, &c., should, of course, receive attention.

Fig. 179 shows the performance of a 1,000 K.V.A. flywheel type generator running at 125 revolutions per minute.

CHAPTER XXIV.

Testing Polyphase Motors.

After a motor has been completed it is necessary to ascertain its general characteristics and in the case of induction motors the case is more complex than with generators for we have not only the primary (stator), but the secondary or rotor, the losses in which are difficult to measure accurately after the machine has been completed, especially if of the squirrel cage type. The various points which require attention are (*a*) $C^2 \times R$ losses; (*b*) friction; (*c*) core losses; (*d*) magnetising current; (*e*) efficiency and power factor; (*f*) starting torque and current corresponding thereto; (*g*) torque at various speeds; (*h*) maximum output; (*i*) drop in speed at full load; (*j*) temperature rise

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after six or more hours run at full load. The first of these (*a*) can be ascertained by measuring the resistance of stator and rotor, when the latter is wound, and the current at the load at which the copper loss is wanted. To obtain the copper loss in the secondary by a measurement of the primary current only, which is the only practical method when the rotor is of the short-circuited type, lock the rotor so that it cannot revolve

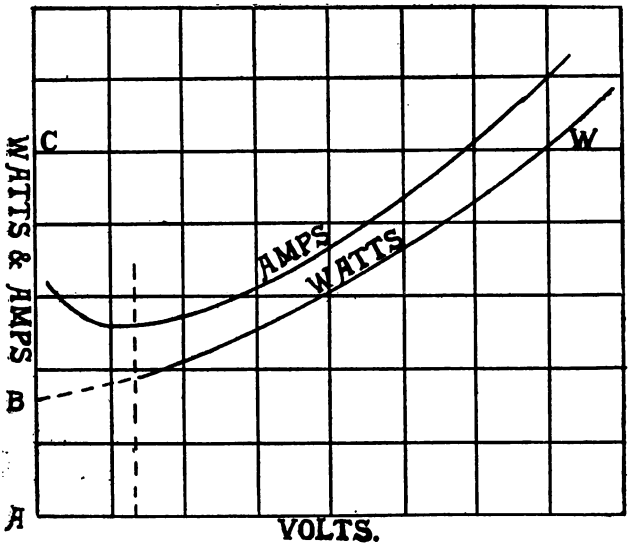

FIG. 180.

and measure the watts input as well as the current; the $C^2 \times R$ losses in primary can now be subtracted from this total, as this can be calculated from the known current and resistance, the core loss must now be subtracted; the method of obtaining this will be described later. The balance is secondary or rotor loss, which, of course, includes both copper and iron, at maximum slip. If the full load slip is known then

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the rotor loss can be approximately determined as proportional thereto. Friction and core loss *b* and *c* can now be ascertained. After the motor has been running light for some time to free the bearings, take the watts and current at various voltages, and plot a curve which will resemble Fig. 180. The watt curve will stop some little distance short of the ordinates, but it is sufficiently accurate to extend the curve to the point B. This stoppage is due to the fact that the product of volts and the watt component of the current is too small to cause the motor to rotate. The watts A to B are the $C^2 \times R$ and friction watts, but as C in the rotor is so small as to be almost negligible in its relation to other losses it may be neglected, and the distance AB considered as friction and stator copper loss only. As C and R are both known, the stator copper loss may be calculated and subtracted leaving only friction. The line C to W, where the line corresponding to full voltage intersects the watt curve, the watts measured from B to C will obviously be core loss, for it is apparent that with full impressed volts the watts taken by the motor light are only those necessary to overcome friction and core losses, *i.e.*, internal losses. From the current observations already made when taking the core and friction losses the magnetising current can be calculated. This, as has already been pointed out (Chap. V., page 40), is at right angles to the watt component of the stator current, and is consequently not capable of direct measurement. At normal E.M.F. the watts are E and the watts per phase are, for a two-phase motor $\frac{w}{2}$ and for a three-phase machine $\frac{w}{3}$; the energy component of the current supplied to the motor is therefore $C = \frac{w}{2 \times e}$ for two-phase and $C = \frac{w}{3 \times e}$ for a three phase motor, where e is the voltage *per phase*. The currents which go to produce the total current are the magnetising component, and the watt component which are at right angles to each

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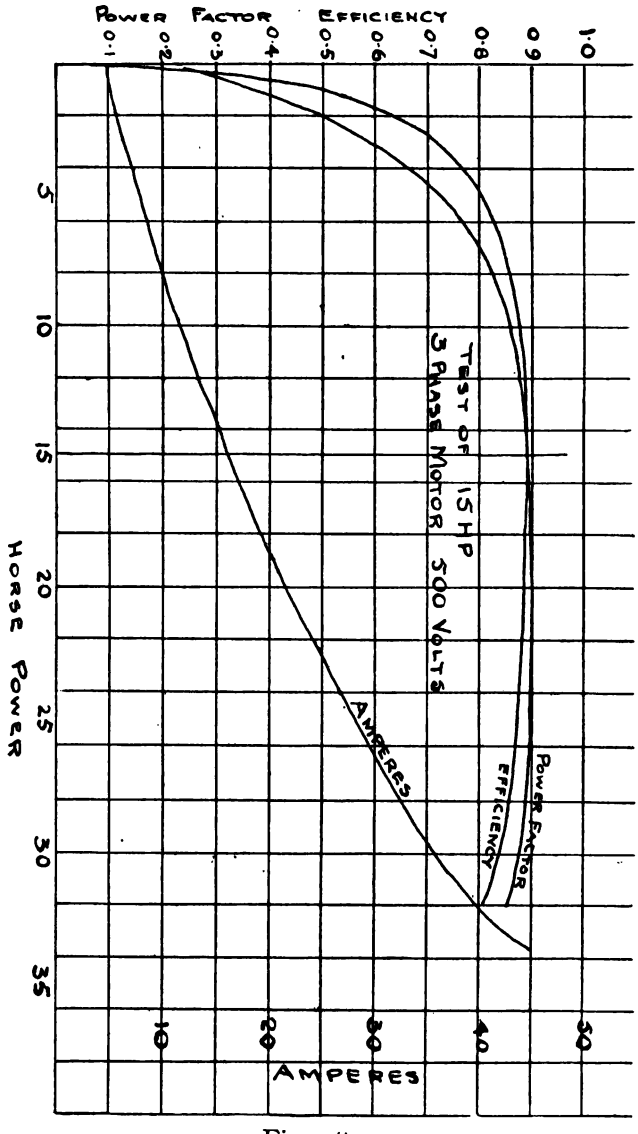

Fig. 181.

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other, the magnetising component is therefore

$$C_m^2 = C_e^2 - C^2$$

where C_m is the magnetising component, C_e is the watt component as already found, and C is the observed amperes at full volts.

The efficiency is the ratio of watts output to watts input, and is most easily calculated by taking the brake horse-power readings, though these are liable to be inaccurate, hence the measurements should be all electrical, as when the load is a direct current dynamo whose efficiency is known, and multiplying the horse-power output of the induction motor by 746, the efficiency is quickly ascertained, while if the apparent input, *i.e.*, current on ammeter × impressed volts is taken, the power factor is calculated as the ratio of true input, as measured by wattmeter, to apparent input.

The initial torque, and current corresponding thereto can be obtained experimentally by means of a brake and simultaneous current readings. The apparent resistance of the windings (impedance) may be taken at this stage, by taking the drop of pressure though the stator winding with a given current at the normal periodicity; this is, of course, R (apparent ohms) $= \frac{E}{C}$

The torque at various speeds may be obtained experimentally by means of a brake and simultaneous speed and current readings; this is useful for crane and similar motors.

The maximum output can be ascertained by running the machine on increasing load till it drops out of step and stops, this corresponds in most cases to from two to three or three and a half times full load. The drop in speed may be measured by taking the revolutions per minute with a speed indicator, and taking the ratio between that and the synchronous speed as calculated from formula 13, page 206, Chap. XX. There are other methods such as, for instance, by marking a coloured disc on the shaft and watching its rotation relative to that of the motor.

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when the disc is illuminated by the light from an arc lamp on the same circuit, the disc will appear to revolve backward, forward, or remain stationary, according as the motor runs slower, faster, or at the speed corresponding to the periodicity of the circuit.

A direct reading slip meter has recently been introduced in the United States; it consists of a small synchronous motor and an indicator which records the difference between the speed of the motor under observation and the synchronous motor. In works test rooms the simplest methods are always best and most reliable, and as such a slip meter involves either a pole changing device to change the number of stator poles from 4 to 6, 8, 10, 12, and so on as circumstances demand, or else a separate slip meter for each synchronous speed; its use is not likely to be extensive.

The temperature rise (t) can be determined, and indeed usually is, by using the motor to drive a direct current generator, and so maintaining full load on the motor. Small motors may be run for four to six hours, as by that time they will have reached their final temperature, though larger machines with a much larger mass of iron will not reach their final temperature for some hours later, as the iron continues to absorb the heat given off by the core and copper.

Full load and temperature tests can also be conveniently made by means of a Hopkinson test. This method, applied to induction motors, was described by Mr. R. W. Weekes in a paper read to the British Association in 1904.*

The reversibility of the induction motor has already been demonstrated (Chap. XXII, p. 270), and it is obvious that by altering the pulleys of two similar machines so that the induction motor running at, say, 5 per cent. below synchronous speed (or whatever the actual slip may be) drives the other machine as an induction generator at five per cent. above synchronous speed, all that is necessary is to supply the losses from an outside

* See also *The Electrical Engineer*, June 17th, 1904.

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source. These are, of course, measured and form the sum of the losses in both machines exactly as in a Hopkinson test of two similar direct current machines. The performance of a 15-horse-power three-phase motor is shown in Fig. 181.

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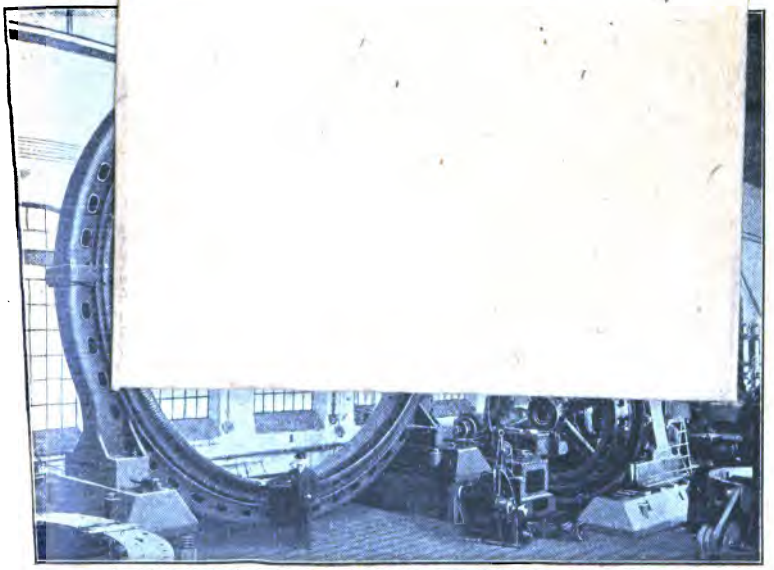

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